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Tham et al.

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[54] METHOD AND APPARATUS FOR CONTROLLING A MEDICAL ANESTHESIA DELIVERY SYSTEM

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[73] Assignee: Ohmeda Inc., Liberty Corner, N.J.

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[51] Int. Cl.[6] A61M 16/01

[52] U.S. Cl. 128/204.22; 128/204.28; 128/203.12; 128/203.14

[58] Field of Search 128/204.22, 203.12, 128/203.16, 204.28, 204.24, 200.21, 203.14

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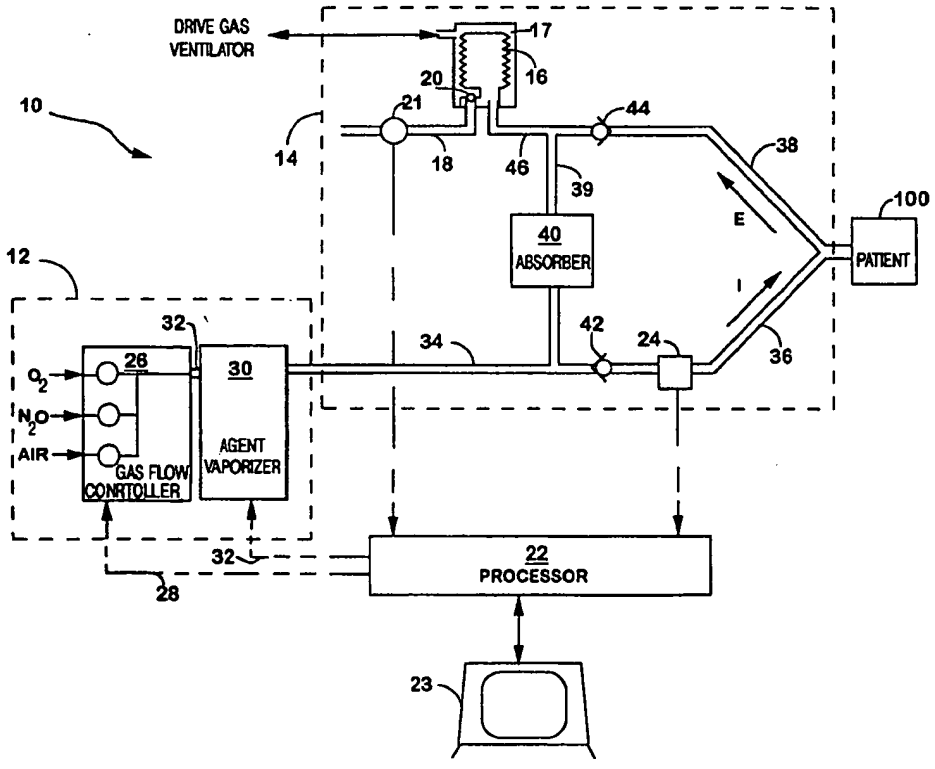
Assistant Examiner—V. Srivastava
Attorney, Agent, or Firm—Roger M. Rathbun; Salvatore P. Pace

[57] ABSTRACT

Efficient management of breathing gases and anesthesia is achieved in an anesthesia delivery system which incorporates a flow minimization routine. The breathing circuit is provided with a pop-off valve and a flow sensor for detecting the pop-off flow. The flow rate of fresh gas into the breathing circuit is controlled, preferably via a digital computer, to minimize the amount of gas exhausted from the circuit. A control routine determines the minimal fresh gas flow necessary to maintain appropriate oxygen concentration, anesthetic agent concentration pop-off flow. A minimum value for the fresh gas flow may also be input to the control system. A fresh gas flow boost routine provides quick responses to charges in the user-set oxygen and agent concentrations. A circuit fill routine provides fresh gas to fill the breathing circuit until pop-off flow is sensed.

20 Claims, 5 Drawing Sheets



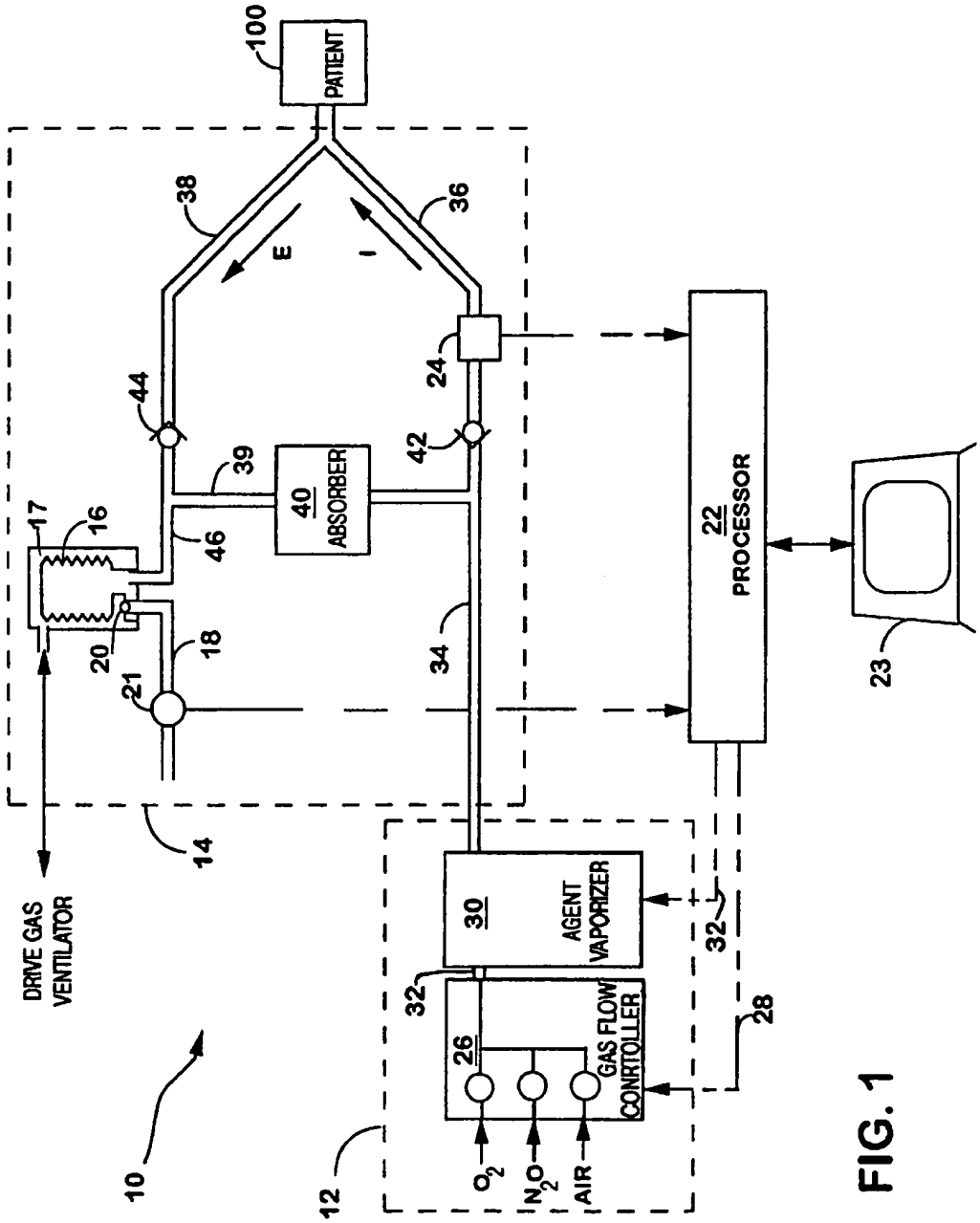

100
PATIENT
38
36
E
I
24
44
42
39
40
ABSORBER
22
PROCESSOR
23
17
16
46
20
18
21
34
14
DRIVE GAS
VENTILATOR
30
AGENT
VAPORIZER
32
32
28
26
GAS FLOW
CONTROLLER
O_2
N_2O
AIR
10
12

FIG. 1

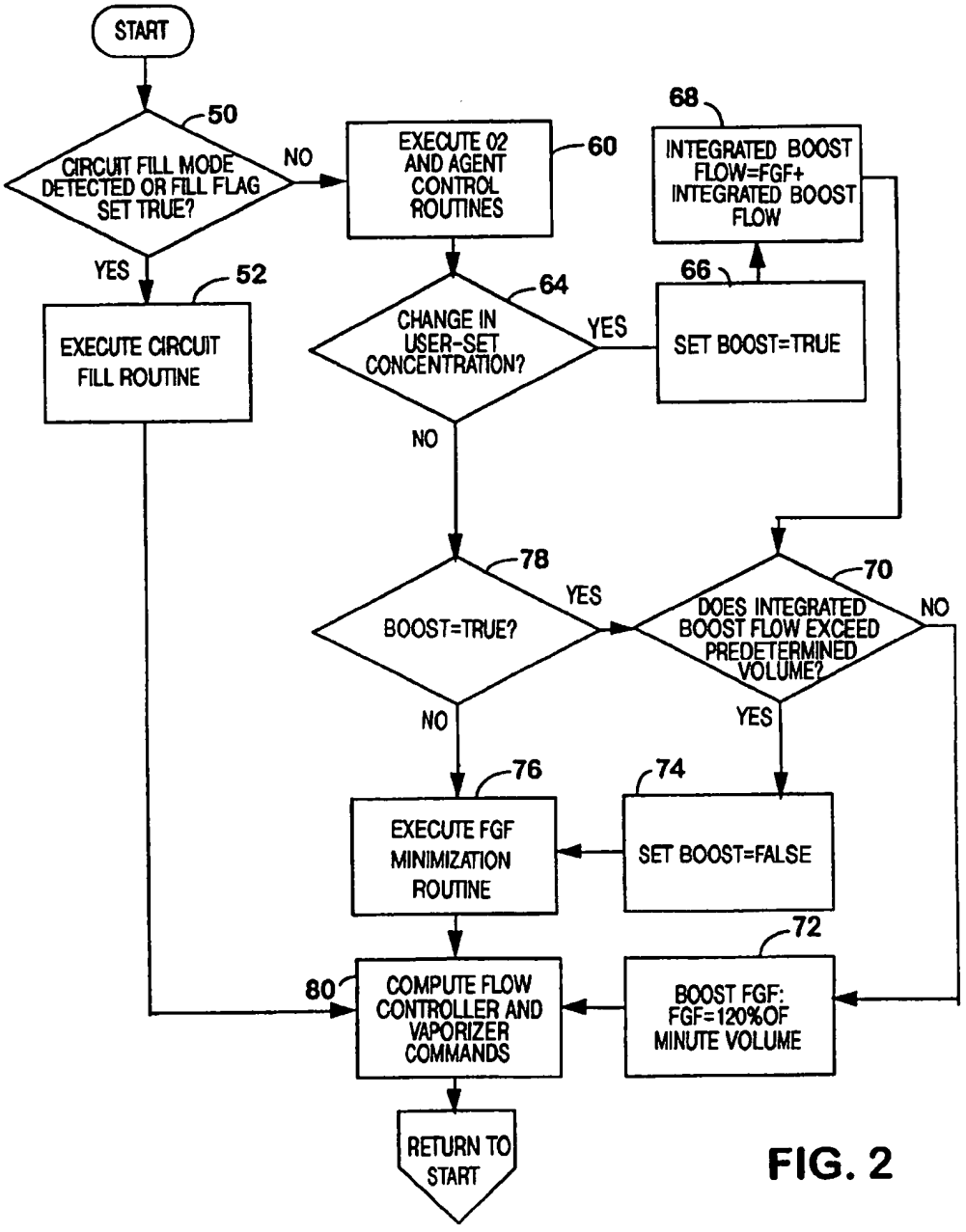

START
50
CIRCUIT FILL MODE DETECTED OR FILL FLAG SET TRUE?
NO
YES
52
EXECUTE CIRCUIT FILL ROUTINE
EXECUTE 02 AND AGENT CONTROL ROUTINES
60
64
CHANGE IN USER-SET CONCENTRATION?
YES
NO
68
INTEGRATED BOOST FLOW=FGF+ INTEGRATED BOOST FLOW
66
SET BOOST=TRUE
78
BOOST=TRUE?
YES
NO
70
DOES INTEGRATED BOOST FLOW EXCEED PREDETERMINED VOLUME?
NO
YES
76
EXECUTE FGF MINIMIZATION ROUTINE
74
SET BOOST=FALSE
72
BOOST FGF: FGF=120%OF MINUTE VOLUME
80
COMPUTE FLOW CONTROLLER AND VAPORIZER COMMANDS
RETURN TO START

FIG. 2

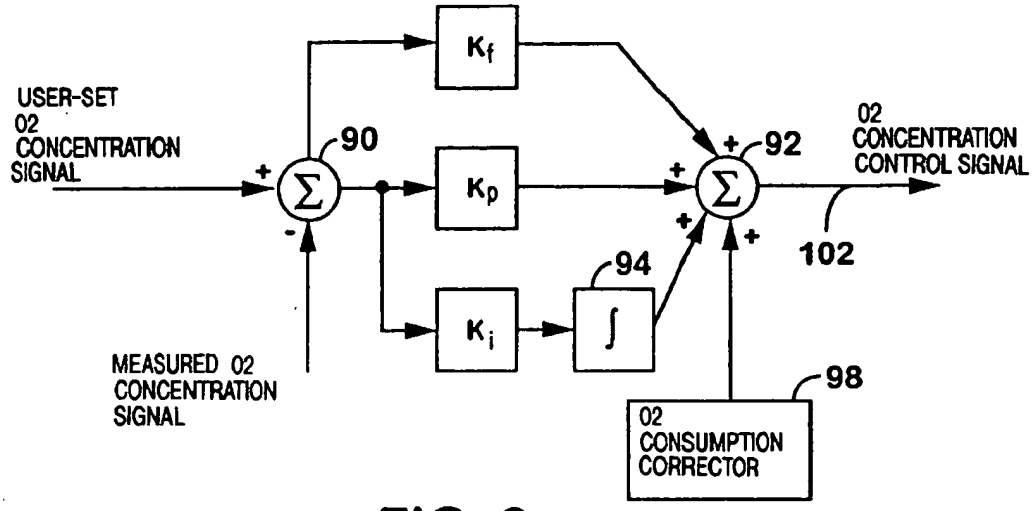

USER-SET
02
CONCENTRATION
SIGNAL
90
K_f
K_p
K_i
94
92
02
CONCENTRATION
CONTROL SIGNAL
102
MEASURED 02
CONCENTRATION
SIGNAL
98
02
CONSUMPTION
CORRECTOR

FIG. 3

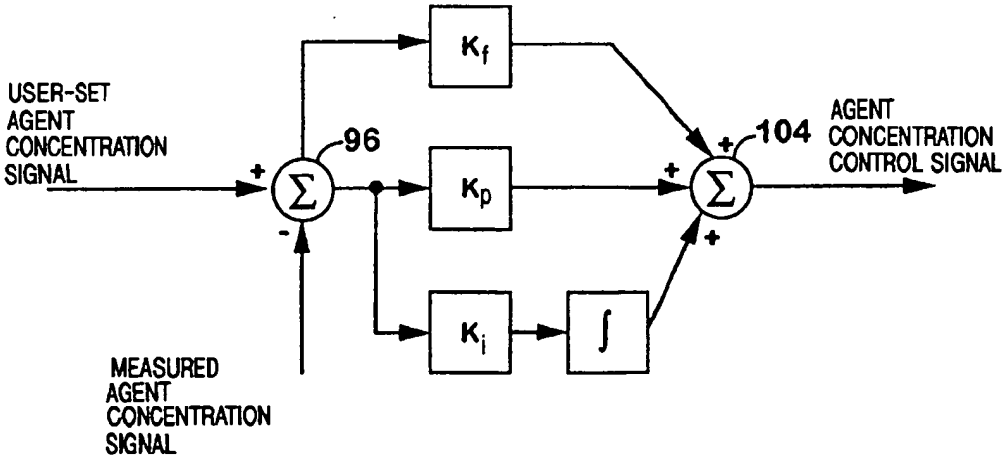

USER-SET
AGENT
CONCENTRATION
SIGNAL
96
K_f
K_p
K_i
104
AGENT
CONCENTRATION
CONTROL SIGNAL
MEASURED
AGENT
CONCENTRATION
SIGNAL

FIG. 4

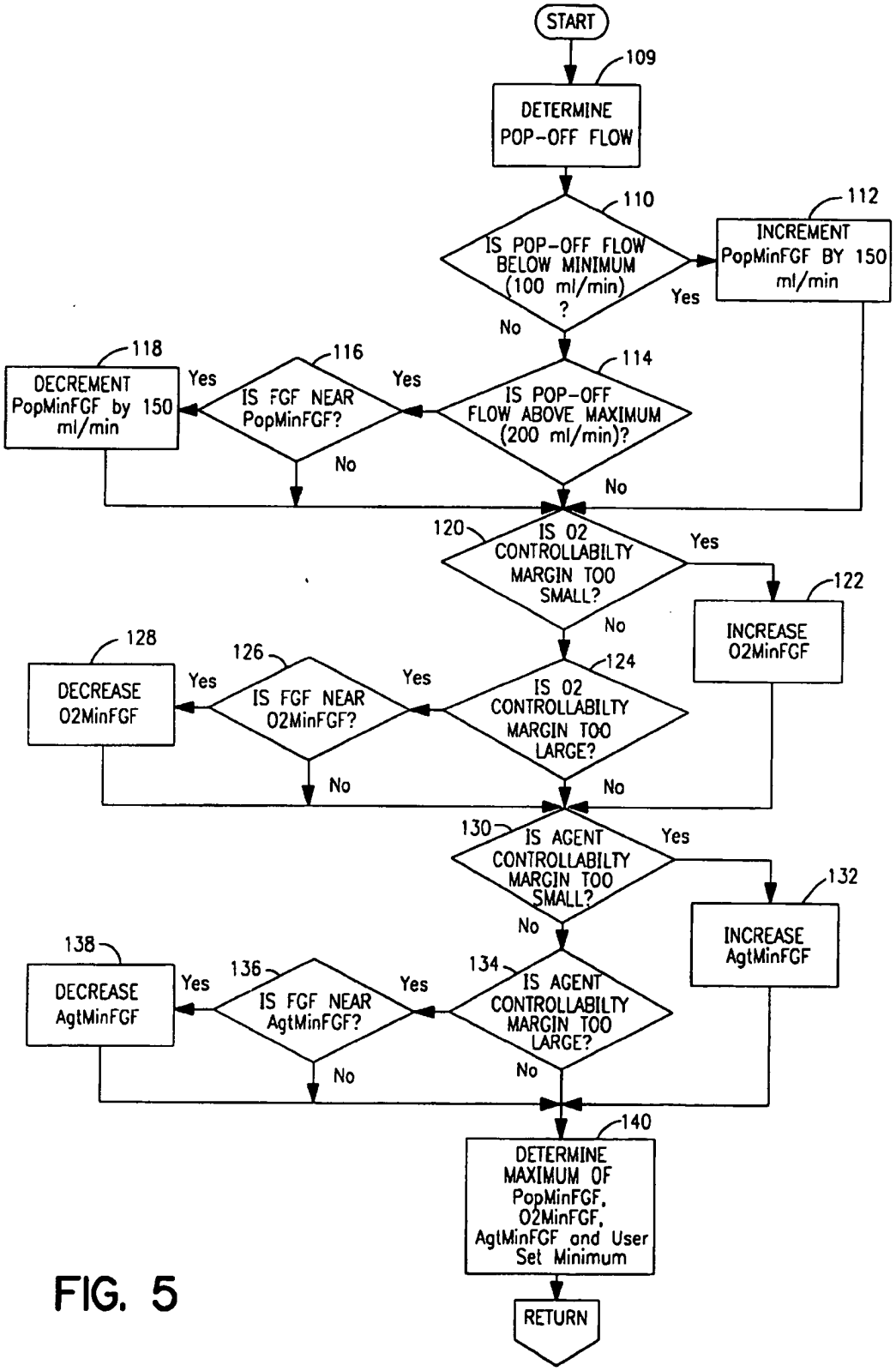

START
109
DETERMINE POP-OFF FLOW
110
IS POP-OFF FLOW BELOW MINIMUM (100 ml/min) ?
Yes
112
INCREMENT PopMinFGF BY 150 ml/min
No
114
IS POP-OFF FLOW ABOVE MAXIMUM (200 ml/min)?
Yes
116
IS FGF NEAR PopMinFGF?
Yes
118
DECREMENT PopMinFGF by 150 ml/min
No
No
120
IS O2 CONTROLLABILTY MARGIN TOO SMALL?
Yes
122
INCREASE O2MinFGF
No
124
IS O2 CONTROLLABILTY MARGIN TOO LARGE?
Yes
126
IS FGF NEAR O2MinFGF?
Yes
128
DECREASE O2MinFGF
No
No
130
IS AGENT CONTROLLABILTY MARGIN TOO SMALL?
Yes
132
INCREASE AgtMinFGF
No
134
IS AGENT CONTROLLABILTY MARGIN TOO LARGE?
Yes
136
IS FGF NEAR AgtMinFGF?
Yes
138
DECREASE AgtMinFGF
No
No
140
DETERMINE MAXIMUM OF PopMinFGF, O2MinFGF, AgtMinFGF and User Set Minimum
RETURN

FIG. 5

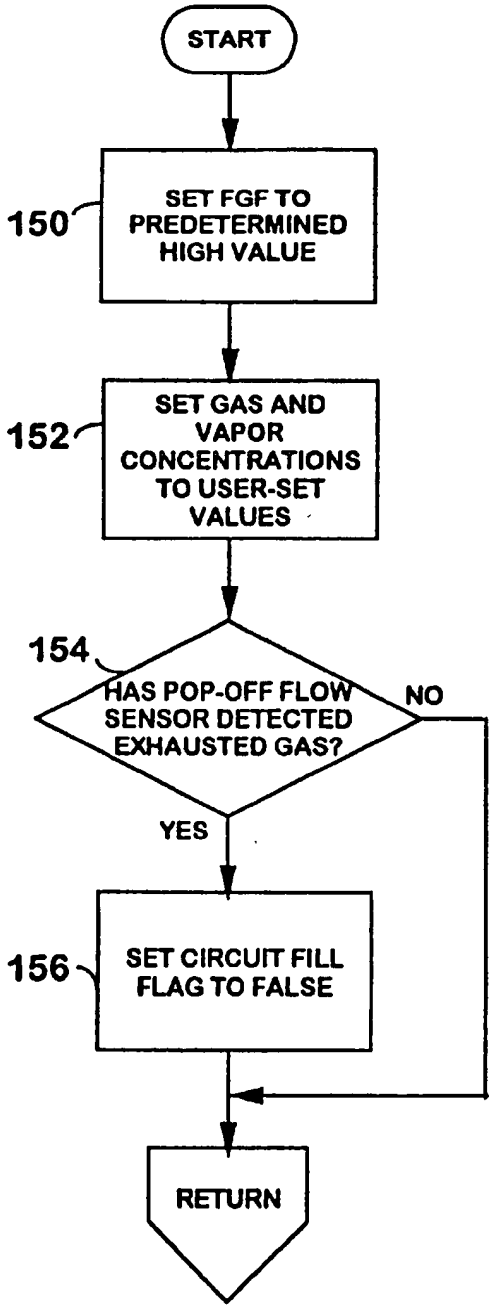

START
150
SET FGF TO PREDETERMINED HIGH VALUE
152
SET GAS AND VAPOR CONCENTRATIONS TO USER-SET VALUES
154
HAS POP-OFF FLOW SENSOR DETECTED EXHAUSTED GAS?
NO
YES
156
SET CIRCUIT FILL FLAG TO FALSE
RETURN

FIG. 6

METHOD AND APPARATUS FOR CONTROLLING A MEDICAL ANESTHESIA DELIVERY SYSTEM

BACKGROUND

The invention relates to medical anesthesia delivery systems for providing breathing gases and anesthesia to a patient. Specifically, the invention relates to a method and apparatus for operating a medical anesthesia delivery system and for controlling the flow and concentration of gases and anesthesia vapor delivered to a patient.

Fundamentally, medical anesthesia delivery systems regulate the flow and mixture of breathing gases inspired and expired by a patient undergoing treatment. Inspired breathing gases typically consist of a mixture of oxygen, nitrous oxide, air and other gases. Anesthesia is administered by clinicians, who command the anesthesia delivery system to control gas and anesthetic concentrations throughout the three phases of patient anesthesia—induction, maintenance and emergence. Each of these phases is characterized by different demands placed on the anesthesia delivery control system. For example, during induction, it is important that high fresh gas flow be supplied to the breathing circuit in order to provide a quick increase in the concentration of breathing gas and anesthesia agent required. At induction, patient uptake of nitrous oxide and volatile anesthesia agent is very high and precise control of the gas flow during this phase is relatively unimportant. On the other hand, during the maintenance and emergence phases, control of the fresh gas flow is more critical. In some practices, during emergence from anesthesia, flow of the anesthetic agent is discontinued, and minimal fresh gas flow is introduced into the breathing circuit to gradually recover the patient from anesthesia. After surgery is completed, fresh gas flows are increased to reduce the anesthetic agent concentration in the inspired mixture and to facilitate a "washout" of anesthetic agent from the patient's bloodstream. Accurate and dependable control of the concentration and flow of gas and anesthetic vapor is thus critical to the function of the anesthesia delivery system and to the safety of the patient undergoing anesthesia.

A typical anesthesia machine mixes the gases which constitute the fresh breathing gas mixture according to operator settings or instructions from a control system. Fresh breathing gas is then conveyed through a vaporizing unit which provides anesthetic vapor to the fresh gas. Fresh gas then enters a breathing circuit which circulates inspired gases to the patient through an inspiratory conduit. Expired gases are conveyed away from the patient via an expiratory conduit. A re-breathing conduit is typically provided to route expired gases from the expiratory conduit back to the inspiratory conduit and is provided with a carbon dioxide absorber for removing carbon dioxide from the re-breathed gas. A bellows assembly is provided in communication with the breathing circuit as a reservoir for breathing gases and to provide the pressure force for ventilator-assisted inspiration and expiration in lieu of spontaneous breathing by the patient or manual bagging by the clinician. A pop-off valve is typically provided in conjunction with the bellows to permit release of excess gas from the breathing circuit. Pop-off flow ensures a full breathing circuit volume.

The advantages of low or minimal fresh gas flow rates into the breathing circuit have long been recognized. Minimal or low fresh gas flow offers the advantages of more efficient management and conservation of fresh gas and anesthetic agent, as well as patient-generated heat and humidity in the breathing gas. Additionally, the effects of leaks and changes in patient uptake are more pronounced, and thus more detectable, in low flow delivery schemes. This permits more careful monitoring of the therapy provided to the patient. Minimal or low fresh gas flow delivery schemes, however, have heretofore presented a number of problems which have resulted in reduced operator confidence.

The response time for low flow systems to reach steady state after a disturbance or change in user-set concentrations varies inversely with the flow rate of fresh gas, that is, changes occur faster with higher flow rates. Thus, a major problem with low or minimal flow delivery schemes, particularly in closed-circuit delivery methods, is that system response to changes in user-set gas and vapor concentrations is unsatisfactory. Low flow delivery schemes are consequently less robust, more susceptible to instability, and more sensitive to disturbances, such as leaks and changes in patient uptake, than higher flow delivery schemes. As a result, clinicians who are accustomed to manually adjusting fresh gas flows according to their own judgment to compensate for or negate the effects of leakage have low confidence in the safety of low or minimal flow systems. Such systems do not allow for adequate clinician control of the fresh gas flow to the breathing circuit.

There have been attempts to reduce fresh gas flows by operating the breathing circuit in closed circuit fashion whereby fresh gas is added to the breathing circuit at the rate at which it is consumed by the patient. Closed-circuit delivery schemes require very precise measurement of the gas volumes in the breathing circuit in order to maintain adequate control thereon. This is a consequence of the fact that the volume of fresh gas that may be used to replenish the breathing circuit, and thus adjust the gas volumes, is limited to the volume lost from the breathing circuit due to patient uptake and, often, leakage. Control techniques for closed-circuit delivery schemes are extremely sensitive to loss in circuit gases through leaks or changes in patient gas exchange. This increases the safety risks associated with the replenishment of the circuit gas volume and maintenance of the ventilatory tidal volume.

Attempts to address the slow response times of closed-circuit delivery systems have done so only at the expense of reduced safety margins or inefficient management of fresh gas flow. U.S. Pat. No. 5,094,235 to Westenskow et al discloses a control system which enables closed-circuit anesthesia delivery systems to quickly respond to changes in user set points. Feedback loops are utilized to control the concentrations of oxygen, carbon dioxide and anesthetic agent concentrations in the breathing circuit based on sensed values. These normally closed control loops may be opened and fresh gas flow increased for a predetermined time in response to a change in the desired user-set concentration for anesthetic agent or gas concentrations. Open-loop high flow operation has the effect of flushing the breathing circuit with fresh gas until the concentration of anesthetic approaches the new desired value. One disadvantage of the device of Westenskow et al is that, once the control loop is closed and fresh gas flow reduced after the new set point has been reached, the system is sluggish in responding to and correcting disturbances in the breathing circuit gas concentrations. Moreover, Westenskow et al offer only limited system responsiveness to disturbances in breathing circuit gas concentrations because their device controls breathing circuit volume using a position sensor for the bellows. Since the amount of fresh gas that may enter the breathing circuit is limited to the amount necessary to refill the bellows, the responsiveness of the control system is limited. Another

disadvantage in the Westenskow et al system is that the user cannot set a minimum fresh gas flow at which the delivery system must operate. Most users are accustomed to providing the delivery of gas and agent therapy in sufficient quantity that excess gases are popped-off from the breathing circuit. While it is desirable for the user to adjust the fresh gas flow to minimize the waste of popped off gases, it is not feasible to eliminate popped off flow entirely and operate the breathing circuit in closed-circuit fashion because closed circuit operation reduces the inherent margin of safety. Consequently, most users rely on their own judgement to strike a balance between economizing the popped off flow of gases and operating the delivery system with an adequate margin of safety. Typically, this is accomplished by setting the total fresh gas flow rate above a minimum value which is selected by the user to yield a preferred amount of popped off flow.

Another problem with prior art anesthesia delivery devices is that they do not provide for efficient management of fresh gas and anesthetic agent during the initial charging of the breathing circuit. Prior art anesthesia delivery devices, during initial charging of the breathing circuit with fresh gas, typically fill the breathing circuit using an oxygen flush, while the operator titrates the anesthesia vapor delivered to the breathing circuit until the proper concentration is achieved. Oxygen flushing methods, however, result in wasted gas and anesthetic agent.

There is thus desired an anesthesia delivery system that solves the aforementioned problems and permits clinicians to control the minimum amount of total fresh gas flow into the breathing circuit according to their own judgment and the clinical need. This provides increased user confidence in the anesthesia delivery system.

There is also desired an anesthesia delivery system control system which permits satisfactory anesthesia delivery system response during low or minimal flow of fresh gas and which is capable of conserving the amount of patient gases exhausted from the breathing circuit.

There is further desired an anesthesia delivery system which is capable of performing a breathing circuit fill operation efficiently and without altering the gas and anesthetic agent concentration inspired by the patient.

It is therefore an objective of the present invention to provide an anesthesia delivery system control scheme which achieves satisfactory automatic control of gas and vapor concentrations at low or minimal fresh gas flows and throughout variations in the rate of flow of fresh gas. It is another object of the invention to provide an anesthesia delivery system which conserves anesthesia delivery system gases, anesthetic agent and patient heat and humidity. It is a further object of the invention to provide an anesthesia delivery system that permits clinicians to set a minimum fresh gas flow to the breathing circuit. It is yet another object of the invention to provide an anesthesia delivery system which performs a circuit fill operation without altering the gas and anesthetic agent concentrations inspired by the patient. These and other objects will be apparent to those of ordinary skill in the art from the foregoing description which is intended to be illustrative of the inventive concepts embodied therein.

SUMMARY OF THE INVENTION

The present invention achieves the aforementioned objectives by providing a semi-closed circuit anesthesia delivery system having integrated control systems for fresh gas flow, flow minimization, oxygen concentration and anesthetic agent concentration. The term "semi-closed" is used because the breathing circuit is not entirely closed, but is provided with a means for minimizing the amount of gas exhausted therefrom. The preferred embodiment of the invention incorporates a breathing circuit having a bellows assembly which is equipped with a pop-off valve which permits gas to be exhausted from the breathing circuit when the gas pressure exceeds a predetermined value. In accordance with the invention, a pop-off flow sensor is provided to monitor the gas flow exhausted through the pop-off valve. The flow minimization control system operates based on signals from the pop-off flow sensor to minimize the amount of flow being exhausted through the pop-off flow valve.

Oxygen and agent concentration routines ensure that sufficient fresh gas flow is supplied to the breathing circuit to maintain user-set oxygen and agent concentrations. The flow minimization routine ensures that only the minimum amount of fresh gas necessary to provide the desired oxygen and anesthetic concentration is provided to the breathing circuit. The control routines are implemented in the form of a programmed digital computer which is electronically linked to the metering valves for the breathing gas components and to oxygen and agent concentration sensors located in the breathing circuit.

In a preferred embodiment, the flow minimization routine determines a first minimum fresh gas flow value necessary to maintain the desired oxygen concentration, a second minimum fresh gas flow value necessary to maintain the desired anesthetic concentration, and a third minimum fresh gas flow value required to maintain the minimum pop-off flow. The routine determines the maximum value of these three minimum values and sets the fresh gas flow to a value corresponding to that maximum. Thus, the fresh gas flow, and the gas exhausted from the breathing circuit, are kept as low as possible; yet the control routine maintains the desired gas and anesthetic concentrations in the breathing circuit.

A fresh gas flow boost routine is provided to reduce the time necessary for the gas and anesthesia concentrations in the breathing circuit to respond to a change in the user-set values. During the fresh gas flow boost, the flow minimization routine is bypassed. The fresh gas flow is boosted to a high value until a predetermined volume, sufficient to refill the breathing circuit, has been flowed.

In order to enhance operator confidence in the anesthesia delivery device of the present invention, the control routine may incorporate a user-set minimum fresh gas flow value. The user-set minimum value constitutes a fourth minimum value to be used in the flow minimization routine described above. For example, if the user-set value (the fourth minimum value) exceeds the values for the fresh gas flow necessary to maintain the oxygen concentration, anesthetic concentration, and minimum pop-off flow (the first, second and third minimum values), then the user-set minimum is determinative of the actual fresh gas flow. In other words, the user-set value represents a "floor" below which the fresh gas flow is not permitted to go.

A circuit fill routine is also provided for minimizing the waste of gas and anesthesia during the initial charging of the empty breathing circuit with fresh gas. When the operator selects the circuit fill mode, the metering valves for the component gases are controlled to provide fresh gas, at a sufficiently high flow rate and having the desired concentrations, to the breathing circuit. The routine monitors the pop-off flow sensor such that when the pop-off flow sensor detects exhausted gas, the fresh gas flow is reduced and the routine proceeds into the fresh gas flow minimization portion.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic showing the elements of a anesthesia delivery system according to the present invention.

FIG. 2 is a flow diagram of an anesthesia delivery system control routine according to the present invention.

FIGS. 3 and 4 are control block diagrams for the oxygen and anesthetic control systems according to the present invention.

FIG. 5 is a flow diagram of a flow minimization routine according to the present invention.

FIG. 6 is a flow diagram of a circuit fill routine according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. 1, an anesthesia delivery system **10** according to the present invention comprises a fresh gas supply **12**, which provides fresh gas to breathing circuit **14**. Breathing circuit **14** includes inspiratory conduit **36**, expiratory conduit **38** and re-breathing conduit **39**. Expiratory conduit **38** is in pneumatic communication with the interior of bellows **16**, which is provided with a pop-off valve **20** and pop-off flow conduit **18**. Pop-off flow sensor **21** generates a signal corresponding to the pop-off flow in conduit **18**. Processor **22** communicates electronically with fresh gas supply **12**, pop-off flow sensor, and breathing circuit **14** via sensors **24**, as will be described below.

Fresh gas supply **12** includes sources for oxygen, nitrous oxide, air, or other gases as is conventionally known. These sources provide gas to the gas flow controller **26**, which includes computer controlled valves to meter the component gases according to signals on data bus **28** to processor **22**. Mixed gas flow is conveyed to agent vaporizer **30**, which provides anesthetic vapor to the mixed gas according to signals on data bus **32**. The mixed gas/anesthetic vapor mixture is then conveyed to breathing circuit **14**.

Breathing circuit **14** functions to deliver inspiratory gas to the patient **100** and deliver expiratory gases from the patient. Fresh gas enters breathing circuit **14** via inlet conduit **34** and is then conveyed to the patient **100** via inspiratory limb **36**. As will be described, re-breathed gas is mixed with the fresh gas prior to its being inspired by patient **100**. Expiratory limb **38** conveys expiratory gases away from the patient. A wye-piece is provided at the junction of the inspiratory limb and the expiratory limb for connection to the patient in a known manner. Carbon dioxide absorber **40** communicates with inspiratory conduit **36** and expiratory conduit **38** via re-breathing conduit **39** and functions to absorb carbon dioxide from the gases in the breathing circuit. During inspiration, flow in inspiratory conduit **36** is in the direction of arrow I and there is no flow in expiratory conduit **38**. Rebreathed gases, after passing through absorber **40**, are mixed with fresh gas in conduit **34** and conveyed to inspiratory conduit **36**. During expiration, flow in expiratory conduit **38** is in the direction of arrow E and there is no flow in inspiratory conduit **36**. Inspiratory check valve **42** and expiratory check valve **44** ensure unidirectional flow in the inspiratory limb **36** and expiratory limb **38**, respectively.

Bellows **16**, as well as the volumes inside bellows conduit **46** and pop-off flow conduit **18**, provide a reservoir for breathing gases. As is known, the exterior of bellows **16** may be subject to driving gases which are regulated by a drive gas ventilator in a known manner. As a conventional alternative to bellows **16**, a manually operated bag (not shown) may be used.

Pop-off valve **20** includes a relief-type valve which communicates pneumatically with the interior space of bellows **16** and with the exterior space **17** of bellows **16**. The relief valve is set to release gas from the breathing circuit **14** when a predetermined pressure differential exists across the valve, that is, when the pressure of gas in the bellows interior, and thus in the breathing circuit, exceed the pressure of gas in exterior space **17**. Thus, when bellows reaches its maximum height and volume, additional gas flowing from breathing circuit **14** into bellows **16** will increase the pressure on the bellows interior, while the pressure on the bellows exterior remains controlled by the drive gas ventilator. A differential pressure will therefore develop across pop-off flow valve **20** and gas will be released from the breathing circuit **14**. Pop-off flow sensor **21** which generates a signal corresponding to the flow of gas released from pop-off valve **20** and communicates that signal to processor **22**.

In operation, the breathing circuit is initially primed to fill its volume, and that of bellows **16** and conduits **46** and **20**, with fresh gas. Pop-off flow sensor **21** detects the full volume condition in the breathing circuit **14**. Patient inspiration, either mechanical or spontaneous, is characterized by compression of bellows **16** and inspired gas flow from the bellows through absorber **40** and inspiratory limb **36**, in the direction of arrow I, into the patient breathing tract. During inspiration, expiratory check valve **44** prevents flow from bellows **16** into expiratory limb **38**. Fresh gas is provided from supply **12** to breathing circuit **14** as dictated by the control system according to the present invention. Thus, the inspired gas will comprise a mixture of fresh gas and re-breathed gas, depending on the commands issued to the gas flow controller **28** and agent vaporizer **32** from processor **22** in a manner to be described below.

Patient expiration is characterized by expansion of bellows **16** as expired gases flow from the patient breathing tract through expiratory limb **38** into bellows **16**. During expiration, inspiratory check valve **44** prevents the flow of gases from inspiratory limb **36** into conduit **34** and re-breathing conduit **39**. During expiration, fresh gas (if continuously flowing) flows into absorber **40** and conduit **39** to add to the expansion of bellows **16**. Inspiration and expiration may occur mechanically, that is, where the driving force for patient breathing are provided by bellows **16**, or spontaneously, where the driving force for patient breathing originates in the muscular forces within the patient's body.

FIG. 2 is a flow chart depicting the logic flow of an algorithm for controlling a anesthesia delivery system according to the present invention. As will be apparent to those of ordinary skill, the algorithm may be implemented with a digital computer using any conventional programming language. At decision block **50**, the routine determines if the circuit fill mode of operation has been selected. If so, the circuit fill routine is executed as represented by block **52** and as explained below with reference to FIG. **6**. Block **60** represents software routines for the oxygen and anesthetic agent controllers, respectively, which are proportional-integral controllers using feed forward as will be explained below with reference to FIG. **3**. At decision block **64**, a determination is made as to whether the user-set values for oxygen or agent concentration have changed since the previous execution of the algorithm according to signals transmitted to processor **22** (FIG. 1) from user interface **23** (FIG. 1). If a change in the user-set value is detected, a fresh gas boost routine is invoked as the program branches to **66**, setting logical flag BOOST to a TRUE value. At **68**, an integration is performed whereby the fresh gas flow (FGF)

is integrated over the duration of the boost. This integrated boost flow corresponds to a high flow of fresh gas introduced into the breathing circuit from the supply **14** (FIG. 1). At **70**, a determination is made as to whether the integrated boost flow exceeds a value corresponding to a constant volume dependent on the bellows and absorber volumes. If the integrated boost flow is less than or equal to the absorber volume multiplied by a constant, the fresh gas flow is boosted (or the boost continues if already invoked) at **72**. Preferably, the fresh gas flow is boosted to a value of 120% of the minute volume, which is the volume of gas delivered to or expired by the patient over during one minute. This boost flow has the effect of charging the breathing circuit with fresh gas at the new desired gas concentrations. The minute volume is typically measured by the ventilator flow monitoring devices. The routine then computes the flow and controller vaporizer commands, as will be described, at **80** and loops back to the beginning to re-execute.

While the integrated boost flow remains below the absorber volume multiplied by a constant, BOOST will remain TRUE and the fresh gas flow will remain set equal to 120% of the minute volume. As can be seen from FIG. **2**, the FGF Minimization routine **76** will be bypassed during the fresh gas flow boost. The boost is terminated when the integrated boost flow exceeds the absorber volume multiplied by a constant, whereby the routine branches to **74**, setting BOOST to a FALSE value. The FGF Minimization routine is then invoked at **76** and the flow controller and vaporizer commands computed at **80**.

Oxygen and Agent Concentration Control

FIGS. **3** and **4** illustrate control diagrams for the oxygen and agent concentration control routines, respectively. These control systems utilize command signals from user interface **23** (FIG. **1**) corresponding to desired values for the oxygen and agent concentrations. The actual values of the concentrations are detected via sensors **24** (FIG. **1**) in the breathing circuit. Both control systems utilize proportional/integral controllers with command feedforward to minimize the difference between the user set value and the measured concentration in the breathing circuit.

Referring to FIG. **3**, the measured O_2 concentration is subtracted from the user-set O2 command at summation block **90**. The resultant is fed forward through feed forward gain K_f (preferably set to a value of 1.0). Proportional gain K_p and integral gain K_i are preferably determined as follows:

$$K_p = C1 \times \text{Minute Volume}/FGF$$

$$K_i = C2 \times \text{Minute Volume}/FGF$$

where C1 is a constant, for example 0.4, and C2 is a constant, preferably 0.002. The Minute Volume and FGF values are obtained from the ventilator and computed from the delivery of the mixer and vaporizer, respectively, where FGF equals the previously commanded total fresh gas flow and MV equals the user-set minute volume of the ventilator, which is typically measured by the ventilator.

Summation block **92**, combines the resultant signals from the feedforward gain K_f, proportional gain K_p, and integral gain K_i and O_2 consumption corrector **98** to yield an O_2 concentration control command **102**. Integrator **94** is off when large changes are commanded by the user and on when the difference between the user set O_2 concentration and the measured O_2 concentration is small.

Oxygen consumption corrector **98** functions to compensate for differences in the concentration of oxygen in the rebreathed and inspired gas. As discussed above with reference to FIG. **1**, during patient inspiration rebreathed gases may be combined with fresh gas in the inspiratory limb. The rebreathed gas may contain less oxygen than the gas in the inspiratory limb because of oxygen consumed by the patient. Under such conditions, the oxygen concentration in the inspiratory limb will decrease as the rebreathed gas is combined with the gas in the inspiratory limb. Preferably, the O_2 Consumption Corrector provides a command in accordance with the function:

$$O_2 \text{ Consumption Correction} = 0.04 * \text{Minute Volume} * (1/FGF * 1.0/MV)$$

Furthermore, the value of the output to summation block **92** is limited between 0.0 and (100%—the maximum deliverable oxygen concentration).

Referring to FIG. **4**, the agent concentration control system incorporates a proportional-integral controller utilizing feed forward. The measured agent concentration signal is subtracted from the user-set agent concentration signal at summation block **96**. Gain Kf is equal to 1.0. Proportional gain Kp, and integral gain Ki are determined as follows:

$$Kp = C3 * \text{Minute Volume}/FGF$$

$$Ki = C4 * \text{Minute Volume}/FGF$$

where C3 is a constant, preferably 0.5, and C4 is a constant, preferably 0.0025.

The gains are summed at block **104** to yield the agent concentration control command. As in the O_2 concentration control system, the integrator **106** is off when large changes are commanded by the user and on when the difference between the user set agent concentration and the measured agent concentration is small.

Fresh Gas Flow Minimization

The fresh gas flow minimization routine determines the minimum amount of fresh gas flow required to maintain the breathing circuit volume, the user set oxygen and agent concentrations in the breathing circuit, and the user-set minimum fresh gas flow if the anesthesia delivery system is operating in a minimum fresh gas flow mode. Pop-off flow sensor **21**, processor **22**, sensors **24**, gas flow controller **26** and agent vaporizer comprise a means for minimizing the pop-off flow, as will be described. Referring to FIG. **5**, at block **110**, the pop-off flow is measured and a determination is made as to whether flow is too small. Preferably, the minimum allowable flow value is about 100 ml/min. If the pop-off flow is below this value, the variable PopMinFGF, which corresponds to the minimum amount of fresh gas flow required to sustain permissible pop-off flow, is incremented at **112** by a constant value, preferably 150 ml/min. At **114**, a determination is made as to whether the pop-off flow is above a predetermined maximum value. Preferably, the maximum allowable flow value is about 200 ml/min. If the pop-off flow is above the maximum, the routine branches to decision block **116**, to determine if the fresh gas flow rate is near the value for PopMinFGF. If so, the value for PopMinFGF is decreased by a predetermined constant value, preferably 150 ml/min at block **118** before the routine continues.

The criterion at block **116** is necessary to prevent a zero pop-off flow condition that might otherwise develop in the case where significant flow is being exhausted from the pop-off valve, but the actual fresh gas flow is not at the value

corresponding to PopMinFGF. The value for FGF is tested to be within 100 ml/min of the value for PopMinFGF to ensure that the minimum being evaluated is the correct "floor" at which the minimum FGF should be set.

Once the value for PopMinFGF is determined, the routine continues to block **120**, which marks the beginning of the determination for the O_2MinFGF, which is the minimum fresh gas flow required to accomplish the Oxygen Concentration Command generated by the control system described above with reference to FIG. **3**. The routine determines if the oxygen concentration controllability margin is too small. That is, whether the current value for O_2MinFGF provides an adequate margin for the oxygen concentration control system to respond to disturbances that might occur within one cycle of the routine. If the margin is determined to be too small, the value of O_2MinFGF is gradually increased by an incremental amount in order to improve the controllability margin.

If a 30% margin of controllability is desirable, for example, the decision at **120** would be made by first determining a desired concentration control command (DCC) according to the formula:

$$DCC=0.70*(100\%-USC)+USC \quad (5)$$

where USC is the User-Set Oxygen Concentration Command. The routine branches to block **122** to increase the value of O_2MinFGF if either of the following conditions are true:

$$OCC>=(DCC+10\%);\ \text{or}$$

$$OCC=100\%\ \text{AND}\ USC<100\%$$

OCC represents the current O_2 Concentration Control Command. The second condition corresponds to the zero-margin control state. If neither of the above conditions are satisfied, the block **122** is bypassed. The increase in the value of O_2MinFGF at block **122** provides added controllability margin if necessary and is accomplished using the following relationship:

$$O_2MinFGF=O_2MinFGF+(OCC-DCC)*FGF\ O_2Incremental$$

where FGF O_2Incremental is a constant value, preferably 5 ml/min and OCC and DCC are defined above.

Block **124** determines if the controllability margin provided by the current fresh gas flow rate is too large. The desired concentration command is computed as in formula (5) above. The value of O_2MinFGF is decreased only if two conditions are satisfied: OCC<(DCC−10%) and the value for O_2MinFGF is near the current fresh gas flow, i.e., within 100 ml/min, as represented by block **126**. The latter condition is necessary to prevent the value of O_2MinFGF from being decremented when O_2MinFGF is not the "floor" that needs to be adjusted. If both of these conditions are satisfied, the value of O_2MinFGF is decreased according to the formula:

$$O_2MinFGF=O_2MinFGF-(DCC-OCC)*FGF\ O_2Incremental$$

where FGF O_2Incremental is a constant, preferably 5 ml/min.

Block **130** determines if the controllability margin provided by the current fresh gas flow rate is too small, i.e, whether the current value for AgtMinFGF provides an adequate margin for the anesthetic agent concentration control system to respond to disturbances that might occur within one cycle of the routine. The routine determines if the agent concentration controllability margin is too small. If the controllability margin is determined to be too small, the value of AgtMinFGF is incremented at block **132** in order to improve the controllability margin.

The decision at **130** is evaluated by first computing a desired concentration control command (DCC) as follows:

$$DCC=0.90*FSV \quad (6)$$

where FSV is the agent concentration command corresponding to the full-scale value of the vaporizer. The agent concentration command (ACC) is evaluated according to the following criteria:

$$ACC>=(DCC+0.10*FSV)$$

$$ACC=FSV\ \text{and}\ USC<FSV$$

If either of the above conditions are true, the routine branches to block **132** to increase the value of AgtMinFGF according to the formula:

$$AgtMinFGF=FGF+(ACC-DCC)*FGFAgtIncremental$$

where FGFAgtIncremental is a constant, preferably 5 ml/min.

Block **134** determines if the controllability margin is too large and thus whether the value for AgtMinFGF may be further decreased. A desired concentration command is computed according to formula (6) above. The value of AgtMinFGF is decreased at **138** if both of the following conditions are satisfied: ACC<(DCC−0.10*FSV) and the value for AgtMinFGF is approximately equal to the FGF, i.e., within 100 ml/min. as represented by block **136**. If these two conditions are not satisfied, the routine continues without decreasing the value of AgtMinFGF. The decrease in AgtMinFGF is computed as follows:

$$AgtMinFGF=FGF-(ACC-DCC)*FGFAgtIncremental$$

where FGFAgtIncremental is a constant, preferably 5 ml/min.

Block **140** corresponds to the computation of the fresh gas flow command based on the computed values of PopMinFGF, O_2MinFGF, AgtMinFGF and a User-Set minimum for the fresh gas flow. The routine sets the minimum fresh gas flow command MinFGF to the maximum of these computed minimums. The resulting maximum value is utilized to control the fresh gas flow FGF according to the following s-domain transfer functions:

If FGF>=0.30 *Minute Volume then

$$FGF=\frac{MinFGF}{(Tau*s+1)}$$

$$\text{where Tau}=\frac{K_t}{(FGF-MinFGF)}$$

and K_t=a constant, preferably 75 sec*L/min.

If 1.0 L/min<FGF<0.30 * Minute Volume then

$$FGF = \frac{MinFGF}{(t/1.5 * s + 1)}$$

If FGF<1.0 L/min then

$$FGF = \frac{MinFGF}{(t/3.0 * s + 1)}$$

Flow Controller and Vaporizer Command Computation

As represented by block **80** in FIG. **2**, the flow controller and vaporizer commands are computed based on the oxygen concentration control command and the fresh gas flow command. If N2O or He are used as the balance gas, the O_2 gas flow command is computed as follows:

O_2 Gas Flow Controller Command=(O_2 Concentration Control Command) * FGF

If Air is the balance gas, the O_2 gas flow command is computed as follows:

O_2 Gas Flow Controller Command=FGF * ((O_2 Concentration Control Command)-(100%-(Agent Concentration Control Command)) * 21%)/79%

The Balance Flow Command is computed, independent of the balance gas selected as follows:

Balance Gas Flow Controller=FGF * (100%-(Agent Concentration Control Command))-(O_2 Gas Flow Controller Command)

The Agent Vaporizer Command is computed as follows:

Agent Vaporizer Command=Agent Concentration Control Command

Circuit-fill Operation

When the circuit fill is desired, the operator will set the circuit fill flag to TRUE via interface **23** (FIG. **1**). The routine of FIG. **2** will then branch at **50** to the circuit fill routine. Referring to FIG. **6**, the circuit fill routine first sets the fresh gas flow to a predetermined high value (10 L/min.) at block **150**. Contemporaneously, the gas and anesthetic vapor concentrations are set to the user-set valves at **152**. At decision block **154**, a determination is made as to whether pop-off flow sensor **21** (FIG. **1**) has detected exhausted gas. If so, the circuit fill flag is set to a FALSE value and when the circuit fill routine returns to the main routine represented in FIG. **2**, the main routine will branch, at block **50**, back to the O_2 and Agent control routines at **60**. If, on the other hand, the pop-off flow sensor does not detect exhausted gas, the routine of FIG. **6** returns without setting the circuit fill flag to FALSE. The circuit fill routine **52** (FIG. **2**) is executed again and until the circuit fill flag is set to a FALSE value.

Those of ordinary skill will recognize that the above description and embodiments are intended to be exemplary and are not intended to limit the scope of the invention as defined in the appended claims. For example, the control functions utilized in the preferred embodiment, as well as the criterion for determining the controllability margins for the various parameters may be modified without departing from the scope of the invention.

What is claimed is:

1. A medical anesthesia delivery system for administering respiration and anesthesia to a patient comprising:

a) a gas supply for providing fresh breathing gas comprised of a plurality of component gases;

b) an anesthetic agent supply for providing anesthetic agent to said fresh breathing gas;

c) a breathing circuit in communication with said gas supply and said anesthetic agent supply for delivering gas and anesthetic agent mixture to and away from said patient's respiratory track, the breathing circuit including a pop-off valve for releasing a pop-off flow of gas from the breathing circuit in response to a predetermined pressure differential;

d) a flow sensor for determining the flow of the gas from the pop-off valve;

e) control means for controlling the concentration of at least one of said component gases and/or said anesthetic vapor in said breathing circuit, and

f) means to minimize the pop-off flow of gas from said pop-off valve determined by said flow sensor.

2. The anesthesia delivery system of claim **1**, wherein said means for minimizing said pop-off flow comprises means for determining a pop-off minimum fresh gas flow required to maintain a predetermined minimal pop-off flow.

3. The anesthesia delivery system of claim **1**, wherein one of said component gases is oxygen, said anesthesia delivery system further comprising

a) an oxygen sensor for generating a measured oxygen concentration signal representing the concentration of oxygen in said breathing circuit;

b) an oxygen concentration controller for generating an oxygen concentration control command based upon said measured oxygen concentration signal;

c) said means for minimizing said pop-off flow including means for determining an oxygen concentration minimum fresh gas flow based upon said oxygen concentration control command.

4. The anesthesia delivery system of claim **3** wherein said oxygen concentration controller generates said oxygen concentration control command based upon the error between said measured oxygen concentration signal and a user-set concentration command.

5. The anesthesia delivery system of claim **1**, further comprising

a) an anesthetic agent sensor for generating a measured anesthetic agent concentration signal representing the concentration of anesthetic agent in said breathing circuit;

b) an anesthetic agent concentration controller for generating an anesthetic agent concentration control command based upon said measured anesthetic agent concentration signal;

c) said means for minimizing said pop-off flow including means for determining an agent minimum fresh gas flow based upon said anesthetic agent concentration control command.

6. The anesthesia delivery system of claim **5**, wherein said means for minimizing said pop-off flow includes means for adjusting said fresh gas flow to the maximum value of said pop-off, oxygen and agent minimum fresh gas flows.

7. The anesthesia delivery system of claim **5**, further comprising a user interface for permitting a user to input a user-set minimum fresh gas flow, said means for minimizing comprising means for adjusting said fresh gas flow to the maximum value of said pop-off, oxygen, agent and said user-set minimum fresh gas flows.

8. The anesthesia delivery system of claim **5**, wherein said anesthetic agent concentration controller generates an anesthetic concentration control command based upon the error

between said measured anesthetic agent concentration signal and a user-set anesthetic agent concentration command.

9. The anesthesia delivery system of claim 1, wherein said breathing circuit further comprises a bellows in pneumatic communication with said pop-off valve means, said pressure differential being defined by the pressure difference between an interior and an exterior of said bellows.

10. The anesthesia delivery system of claim 1, further comprising a user interface for permitting a user to input a user-set minimum fresh gas flow, said means for minimizing comprising means for maintaining said fresh gas flow above said user-set minimum.

11. A medical anesthesia delivery system for administering respiration and anesthesia to a patient comprising:

a) a gas supply for providing fresh breathing gas comprising a plurality of component gases;

b) an anesthetic agent supply for providing anesthetic agent to said fresh breathing gas;

c) a breathing circuit in communication with said gas supply and said anesthetic agent supply for delivering gas and agent mixture to and away from said patient's respiratory tract, the breathing circuit including a pop-off valve for releasing a pop-off flow of gas from the breathing circuit;

d) flow sensor means for measuring the pop-off flow of gas released from said pop-off valve;

e) user input means for permitting an operator to input desired concentrations for said component gases and said anesthetic agent in said breathing circuit;

f) control means for controlling the concentration of at least one of said component gases in said breathing circuit and including: (i) means for increasing said fresh gas flow by a predetermined volume in response to a change in at least one of said desired concentrations inputted by a user with said user input; and (ii) means for minimizing said pop-off flow measured by said flow sensor means.

12. The anesthesia delivery system of claim 11, wherein said predetermined volume is determined based on an estimated volume of the breathing circuit.

13. The anesthesia delivery system of claim 11, wherein said control means further comprises means for bypassing said means for minimizing during said boost of fresh gas flow.

14. A method of controlling a medical anesthesia delivery system for administering respiration and anesthesia to a patient, the anesthesia delivery system including a gas supply for providing fresh breathing gas comprised of a plurality of component gases, an anesthetic agent supply for providing anesthetic agent to said fresh breathing gas, and a breathing circuit in communication with said gas supply for delivering gas and anesthetic agent mixture to and away from said patient's respiratory tract, the breathing circuit including pop-off valve for releasing a pop-off flow of gas from the breathing circuit in response to a predetermined pressure differential, the method comprising the steps of:

measuring the pop-off flow of gas released from the pop-off valve; and

minimizing said pop-off flow measured in the previous step while controlling the concentration of at least one of said component gases and said anesthetic agent in said breathing circuit.

15. The method of claim 14, wherein said step of minimizing further comprises the steps of:

a) determining a pop-off minimum fresh gas flow required to maintain a predetermined pop-off flow.

16. The method of claim 15, wherein the step of minimizing further comprises:

b) determining a control command for the concentration of at least one of said component gases and said anesthetic agent in said breathing circuit, said control command being based upon the difference between a measured concentration and a desired concentration of said at least one of said component gases and said anesthetic agent; and

c) determining a component gas minimum fresh gas flow required to maintain a desired controllability margin for said control command.

17. The method of claim 16, where said step of minimizing further comprises the steps of:

d) determining an anesthetic agent concentration control command for controlling the concentration of anesthetic agent in said breathing circuit and determining an anesthetic agent minimum fresh gas flow required to maintain a desired controllability margin for said anesthetic agent concentration control command;

e) determining the maximum of said pop-off, said component gas, and said anesthetic agent minimum fresh gas flows.

18. The method of claim 16, wherein said step of minimizing further comprises the steps of:

e) determining the maximum of said pop-off, said component gas, and said anesthetic agent minimum fresh gas flows and a user-set minimum fresh gas flow.

19. A method of controlling a medical anesthesia delivery system for administering respiration and anesthesia to a patient, the anesthesia delivery system including a gas supply for providing fresh breathing gas comprised of a plurality of component gases, an anesthetic agent supply for providing anesthetic agent to said fresh breathing gas, a breathing circuit in communication with said gas supply for delivering gas and anesthetic agent mixture to and away from said patient's respiratory tract, the breathing circuit including pop-off valve for releasing a pop-off flow of gas from the breathing circuit in response to a predetermined pressure differential, and a user interface for permitting a user to input values for desired concentrations of said component gases and said anesthetic agent in said breathing circuit, the method comprising the steps of:

a) changing at least one of said user-input values;

b) increasing the flow rate of fresh gas into said breathing circuit to a value based on the minute volume of gas delivered to the patient in response to the changing of said at least one of said user input values while maintaining or reducing the errors between measured values corresponding to the component gas and anesthetic agent concentrations and said user-set values;

c) monitoring the pop-off flow of gas released from the pop-off valve; and

d) terminating said increased flow rate when said pop-off flow of gas from said pop-off valve monitored in step c) exceeds a predetermined amount;

e) minimizing the fresh gas flow.

20. A medical anesthesia delivery system for administering respiration and anesthesia to a patient comprising:

a) a gas supply for providing fresh breathing gas comprised of a plurality of component gases;

b) an anesthetic agent supply for providing anesthetic agent to said fresh breathing gas;

c) a breathing circuit in communication with said gas supply and said anesthetic agent supply for delivering gas and anesthetic agent mixture to and away from said patient's respiratory tract, the breathing circuit including a pop-off valve for releasing a pop-off flow of gas from the breathing circuit in response to a predetermined pressure differential;

d) gas flow sensor means for monitoring the pop-off flow of gas released from said pop-off valve;

e) means for filling the breathing circuit with said fresh breathing gas and including means for terminating the filling when a predetermined pop-off flow from said pop-off valve is sensed by said gas flow sensor.

* * * * *

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United States Patent [19]

Westenskow et al.

[11] Patent Number: 5,094,235

[45] Date of Patent: Mar. 10, 1992

[54] **ANESTHESIA VENTILATING APPARATUS HAVING A BREATHING CIRCUIT AND CONTROL LOOPS FOR ANESTHETIC GAS COMPONENTS**

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[21] Appl. No.: **349,829**

[22] Filed: **May 10, 1989**

[51] **Int. Cl.**[5] **A61M 16/00**; A62B 7/00; F16K 31/02; G05D 11/02

[52] **U.S. Cl.** **128/204.22**; 128/203.12; 128/205.12; 128/203.25

[58] **Field of Search** 128/203.12, 204.21, 128/204.22, 203.25, 204.25, 205.12

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Primary Examiner—Edgar S. Burr
Assistant Examiner—Kimberly L. Asher
Attorney, Agent, or Firm—Walter Ottesen

[57] **ABSTRACT**

The invention relates to an anesthesia ventilating apparatus having a breathing circuit and a plurality of control loops for the anesthesia gas, the anesthesia agent and the carbon dioxide exhaled by a patient. A disconnect switch is provided for opening and closing the control loop for adjusting the anesthesia agent. When this control loop is opened, a control unit changes the desired value of the anesthetic agent to a desired flushing value thereof. The control unit includes a processor which monitors the time-dependent course of the concentration of the anesthetic agent to determine breathing circuit system parameters and then computes the adjusting parameters of a controller in the control loop for adjusting the anesthetic agent. A method of operating the apparatus is also disclosed.

8 Claims, 3 Drawing Sheets

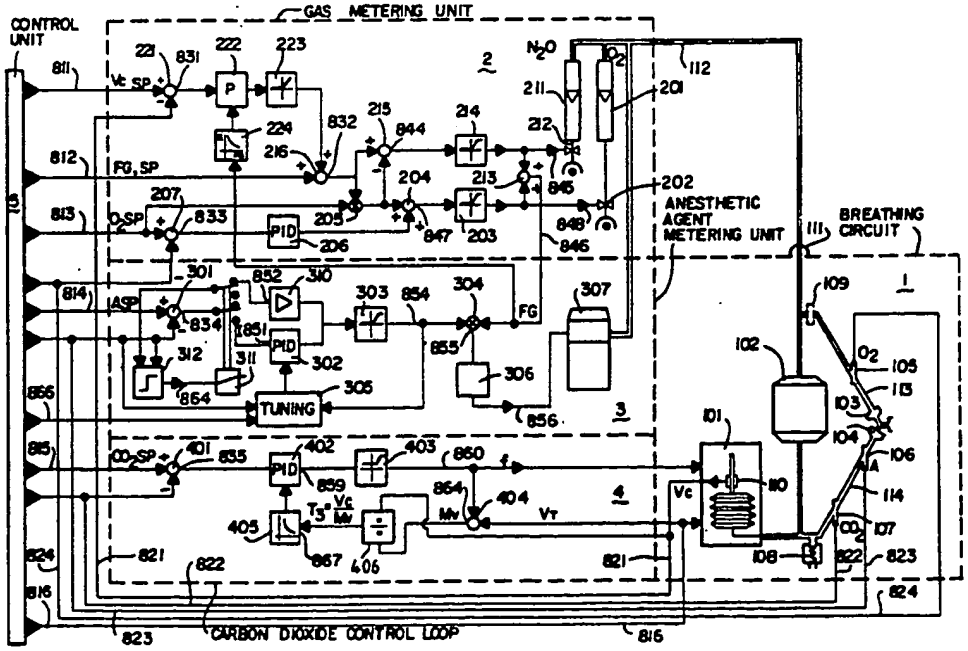


FIG. 1

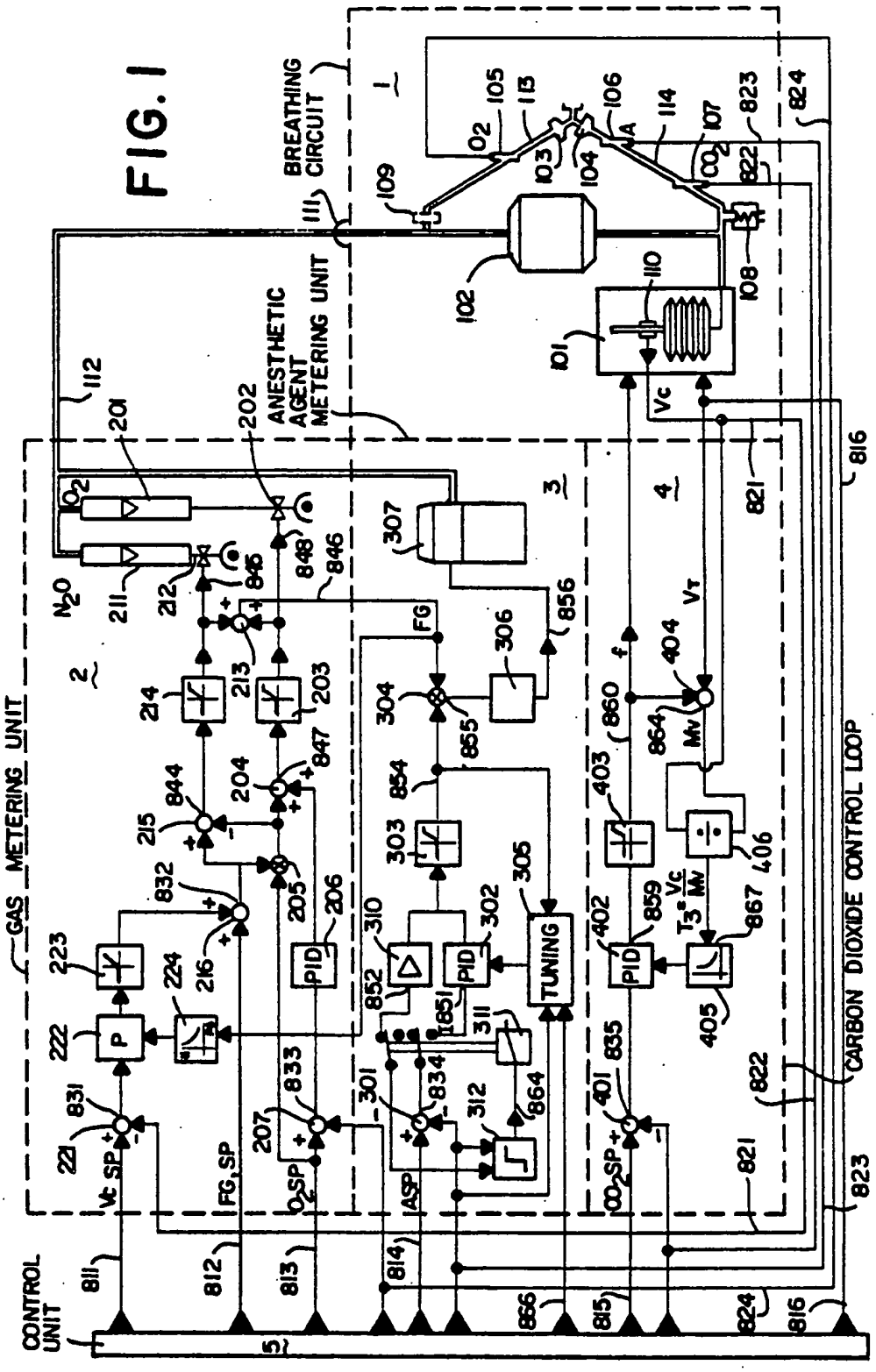
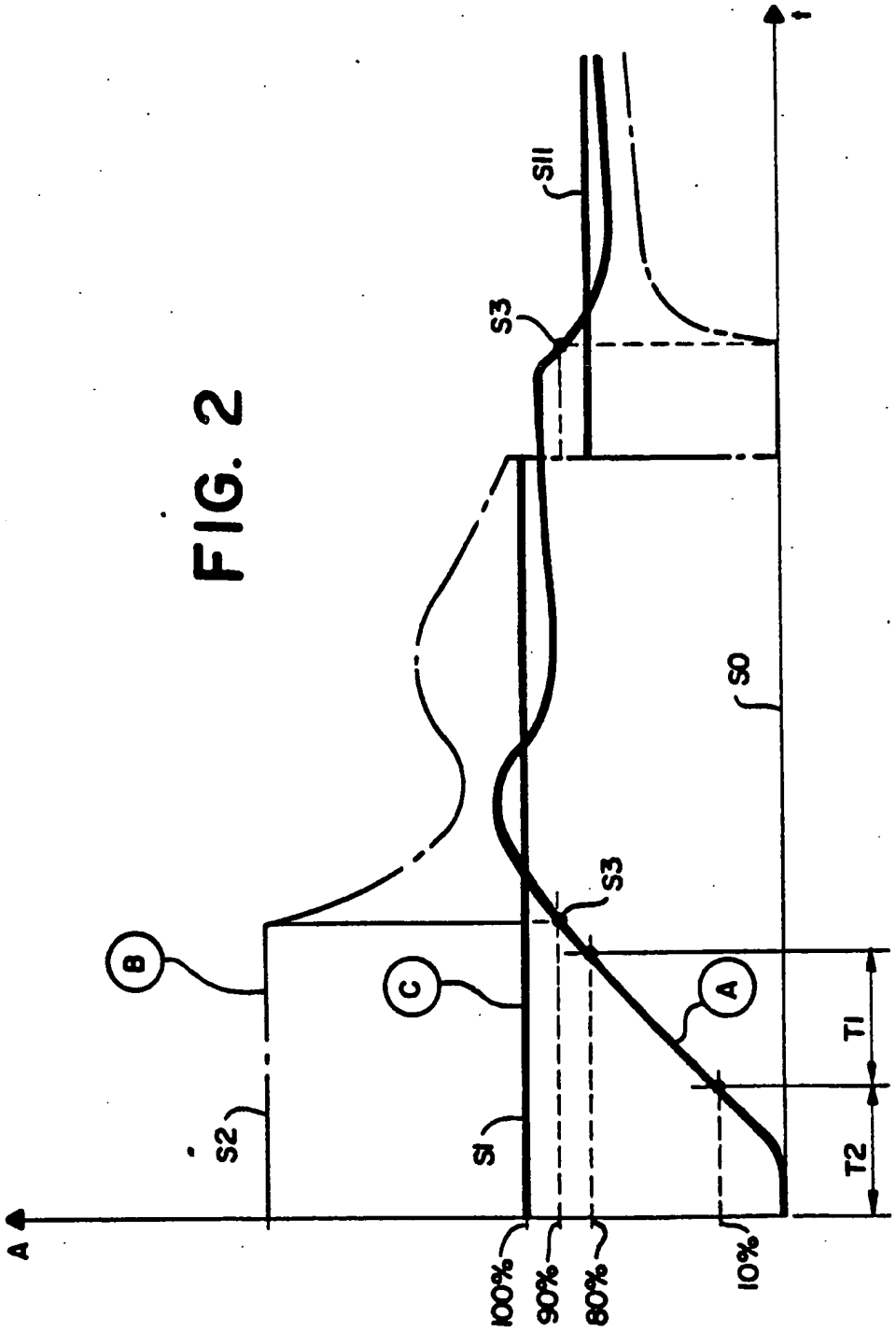
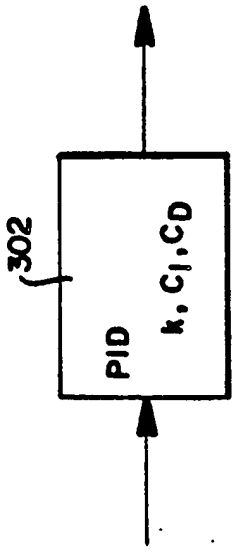

BREATHING CIRCUIT
ANESTHETIC AGENT METERING UNIT
GAS METERING UNIT
CARBON DIOXIDE CONTROL LOOP
CONTROL UNIT
PID
TUNING
P

FIG. 2





$$k = \frac{1,2 \cdot T_I}{(T_2 + T_O)} \quad ; \quad c_I = \frac{0,6 \cdot T_I \cdot T_O}{k\,(T_2 + T_O/2)^2} \quad ; \quad c_D = \frac{0,5 \cdot T_I}{k \quad T_O}$$

$$\frac{0,3 \cdot T_I \cdot T_O}{(T_2 + T_O/2)^2} \quad ; \quad T_O = \frac{1}{\text{BREATHING FREQUENCY } f}$$

FIG. 3

ANESTHESIA VENTILATING APPARATUS HAVING A BREATHING CIRCUIT AND CONTROL LOOPS FOR ANESTHETIC GAS COMPONENTS

FIELD OF THE INVENTION

The invention relates to an anesthesia ventilating apparatus having a breathing circuit wherein the anesthetic gases necessary for the ventilation can be metered and can be influenced via a control loop. The invention also relates to a method for operating the anesthesia ventilating apparatus.

BACKGROUND OF THE INVENTION

An anesthetic ventilating apparatus having a closed breathing circuit is disclosed in European Patent Publication 0 121 255. This anesthesia ventilating apparatus utilizes a complex control loop for metering anesthetic gas in which the anesthetic gas components are sensed by means of appropriate sensors and the sensor signals are utilized for driving a metering unit. At any time during a ventilation, the fill level of the breathing gas in the breathing circuit is determined and the required fresh gas quantity is supplied.

The control loop for metering the anesthetic gas is essentially conceived for maintaining a quasi-stationary operating condition; that is, the previously adjusted concentration values of the anesthetic gas components are maintained pursuant to a determined unchangeable control algorithm and only as much gas is metered as was consumed.

It is a disadvantage with the known anesthesia ventilating apparatus that for a change of the concentration proportion of individual anesthetic gas components such as the anesthetic agent concentration, new values are reached in part only after substantial adjusting times with the measured concentration in the breathing circuit approximating the new desired value asymptotically. This is for many applications intolerable such as for the transition from the induction phase with higher anesthetic agent concentration to the maintenance phase with lesser concentration.

An anesthesia ventilating apparatus having controlled metering of the anesthesia agent vapor is disclosed in the British Journal of Anaesthesia (1983), 55, pages 1065 to 1075. The breathing system supplying the patient with breathing gas is connected to a ventilator for assisted ventilation and is supplied via a gas metering unit with the anesthetic gases: nitrous oxide, oxygen and anesthetic agents. A central microprocessor controlled control unit on the one hand influences the anesthetic agent metering unit in the manner of a desired-value generator and, on the other hand, registers the actual value which is measured with an anesthetic agent sensor in the breathing system downstream of the patient. When adjusting to a new anesthetic agent desired value, the control unit first supplies an actuating-variable signal to the metering unit which is greater by a multiple than the new desired value which is to be set. This first phase takes approximately nine respiratory cycles and has the purpose of determining parameters specific to the system from the spontaneously adjusting anesthetic agent concentrati n change in the breathing system. These parameters and further constants stored in the control unit are combined with each other in order to bring the anesthetic agent concentration in the breathing system closer to the new desired value in a stepwise manner during a second phase which has a duration of approximately 90 respiratory cycles. In the third phase, the anesthetic agent concentration is adjusted to the selected desired value by switching in a controller.

It is a disadvantage with this anesthesia ventilating apparatus that a new desired value for the anesthetic agent concentration is adjustable only after a complex measuring and computing program wherein constants from a table have to be considered and inputted to a control unit in advance. The division into three phases is impractical for the clinical routine. Furthermore, there is no direct coupling between the parameters measured in the first phase and the adjusted values of the anesthetic agent controller which is switched in in the third phase.

SUMMARY OF THE INVENTION

It is an object of the invention to provide an anesthesia ventilating apparatus of the kind described above which is so improved that a changed input desired value of an anesthetic gas component is adjustable in a manner which is optimized with respect to time and wherein the controller of the control loop corresponding thereto is automatically adaptable to the system parameters of the breathing circuit. It is also an object of the invention to provide a method for operating the anesthesia ventilating apparatus.

The method of the invention is applied for operating an anesthesia ventilating apparatus having at least one anesthetic gas control loop with a disconnect switch. The apparatus includes a control unit for adjusting a new anesthetic gas desired value S1 performing the following method steps: switching the disconnect switch into the open position during a predetermined time duration; adjusting the anesthetic gas actuating variable at the metering unit in a discontinuous manner to a flushing desired value S2 deviating from the desired value S1; determining the breathing circuit system parameters T1 and T2 from the time-dependent course of the anesthetic gas concentration measured with the measuring unit in at least one of the branches and computing herefrom at least adjusting parameters for the anesthetic gas controller; and, switching the disconnect switch into the closed position when the anesthetic gas concentration value S3 is reached whereby the anesthetic gas controller influences the metering unit to adjust to the desired value S1.

The advantage of the invention is seen essentially in that the control loop is opened for a specific time duration and the breathing circuit can be flushed with the anesthetic gas to be changed. Only when a concentration value in the vicinity of the new desired value to be adjusted is reached, is the control loop again closed, whereby the controller influences the metering unit of the particular anesthetic gas for setting the new desired value. Furthermore, breathing loop system parameters are determined from the time-dependent course of the anesthetic gas concentration and adjusting parameters are computed herefrom for the anesthetic agent controller. The time-dependent course of the anesthetic gas concentration in the breathing circuit is, for example, dependent upon the following: the inflowing gas quantity of the anesthetic gas component; the volume of the breathing circuit and the gas circulation within the breathing circuit. A controller with a fixed adjustment can provide optimal results for only a specific constellation of parameters. A requirement-tailored adaptation

of the adjusting parameters is computed from the time-dependent course of the concentration. By means of this adaptation, the controller supplies time-optimized adjusting values specifically also when components of the breathing circuit are changed at intervals, for example, by means of adding tubes between patient and ventilating apparatus. Such modifications can be determined by measuring the time-dependent course of the concentration change.

It is advantageous to use the anesthetic agent concentration as an anesthetic gas component since this must in any event be changed as required by the routine anesthesia method. For example, one works with higher anesthetic agent concentration in the inflowing anesthesia gas during the induction phase and with a lesser concentration of anesthetic agents in the maintenance phase. During the recovery phase at the end of an anesthesia, the anesthesia agent concentration is completely reduced down to the value zero. The oxygen concentration in the breathing circuit is a further anesthetic gas component which can be used. The oxygen concentration is changeable in that the breathing circuit is flushed with oxygen or nitrous oxide. In this connection, the concentration of oxygen cannot however drop below the minimum concentration required for ventilation.

For a concentration change, it is advantageous to adjust the actuating variable to a multiple of the desired value (the flushing desired value S2). For a concentration increase, this factor can go up to a multiple of 10 of the desired value; whereas, with a decrease in concentration, this factor can cause a reduction of the actuating variable to the value zero.

After reaching a multiple of 0.9 of the desired value S1, the control circuit is closed for a concentration increase and the controller influences the actuating variable. The anesthetic gas concentration is now controllable to the previously adjusted desired value. For a concentration reduction, the controller is switched in for a 1.1 multiple of the new desired value S11.

It is advantageous to determine the system parameters of the breathing circuit from the time-dependent course of the particular anesthetic gas concentration. These system parameters result essentially from the washout time of the breathing circuit having the changed anesthetic gas parameter and can be influenced by the following: the anesthetic gas flow, the breathing stroke volume, the breathing frequency and the anesthetic gas uptake by the patient. In addition to the anesthetic agent concentration, it is advantageous to also provide control loops for the oxygen concentration, the breathing circuit volume and the carbon dioxide concentration and to make these control loops connectable via coupling members.

These coupling members are suitable to make dependent variables controllable. For example, if the anesthetic gas flow is increased, the anesthetic agent vapor quantity must likewise be added in order to maintain a constant anesthetic agent concentration in the breathing circuit; that is, the anesthetic agent metering pump must add a higher quantity of fluid to the anesthetic gas flow. In addition, it is advantageous to control the sensitivity of individual controllers in dependence upon specific anesthetic gas parameters. For example, for a closed breathing circuit, the breathing circuit volume controller is the determining component for the metering of anesthetic gas into the breathing circuit since only the volume which has been consumed is added. If in contrast, a quantity of anesthetic gas is metered which is a multiple above that which is consumed as is the case for a half-closed breathing circuit, then the breathing circuit volume controller is of secondary importance since the surplus anesthetic gas is released to the ambient via a surplus gas venting valve after each breath. A sensitivity adaptation is likewise provided for the carbon dioxide controller. The amplification factor is adjusted in dependence upon the breathing circuit volume and the minute volume. For higher breathing minute volumes, that is for a more intense ventilation of the patient, the sensitivity is maximal and the carbon dioxide controller reacts immediately to a change in concentration of carbon dioxide measured in the breathing circuit.

A further coupling member is the adaptation circuit for the anesthetic agent controller which impresses the adjusting parameters on the latter with the desired values being supplied by the control unit.

By coupling the control loops, it is intended that the anesthesia ventilating apparatus automatically selects the most advantageous controller constellation in dependence upon the adjusted ventilating parameters.

It is advantageous to make individual coupling members and individual controllers driveable by the control unit. In this manner, the adjusting parameters of the anesthetic agent controller can for example be computed by the control unit and be transmitted via an adaptation circuit. It is also conceivable that further parameters can be taken into the computation of the controller adjusting parameters such as variables related to the patient such as body weight, body size and the like. This can be required if changes in concentration can be carried out only in a limited manner such as in infants.

It is advantageous to control the sequence of desired value inputs by means of the control unit. For example, if several anesthetic gas components are to be changed simultaneously, priorities for the desired values can be determined by the control unit. An advantageous priority sequence could, for example, be to first adjust the oxygen concentration in the breathing circuit with the supply of oxygen. The anesthetic agent concentration is adjusted for the depth of anesthesia with the second priority stage. The carbon dioxide concentration is controllable by influencing the breathing frequency at the ventilator. The volume control circuit is finally activated when all other control loops are in the steady state in order to adjust the breathing circuit volume to the preselected value.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described with reference to the drawings wherein:

FIG. 1 is a schematic block diagram of the breathing circuit having control loops for the anesthetic gas components;

FIG. 2 is a curve showing a jump response when changing the concentration of the anesthetic agent; and,

FIG. 3 shows the determination of the controller parameters k, CI, CD obtained from T1 and T2.

DESCRIPTION OF THE PREFERRED EMBODIMENTS OF THE INVENTION

The anesthesia ventilating apparatus shown in FIG. 1 comprises the breathing circuit 1, the gas metering unit 2 for the anesthetic gas components of oxygen and nitrous oxide, the anesthetic agent metering unit 3, the carbon dioxide control loop 4 and the control unit 5

having an integrated computer portion. The different components are enclosed by a broken line.

The breathing circuit 1 having an uptake branch 113 and an exhale branch 114 takes care of conveying the breathing gas to a patient (not shown). The breathing circuit 1 includes: the ventilator 101 which is preferably configured as a piston-cylinder unit, the carbon dioxide absorber 102 for removing carbon dioxide exhaled by the patient, directional valves (103, 104) for controlling the direction of the breathing gas, sensors (105, 106, 107) for analyzing the components of the anesthetic gas and a surplus gas venting valve 108.

In addition, means are provided for switching a charcoal filter 109 into the breathing circuit 1 as required in order to remove the anesthetic agent delivered by the anesthetic agent metering unit 3 either partially or even completely. This can be necessary when the concentration of the anesthetic agent must be reduced in a short time, for example, during the transition from the induction phase into the maintenance phase of the anesthesia.

The breathing circuit 1 is configured for operation with partial or complete rebreathing whereby a high re-utilization rate of the anesthetic gas is provided. For complete rebreathing, only the gas lost by consumption and leakage must be again delivered.

For analyzing the anesthetic gas components, an oxygen sensor O_2 (105) is provided at the inspiratory end and an anesthetic agent sensor A (106) and a carbon dioxide sensor CO_2 (107) are provided at the expiratory end.

Anesthetic gas from the gas metering unit 2 and the anesthetic agent metering unit 3 flows via the anesthetic gas connection 111 into the breathing circuit 1. Surplus gas can be removed via the surplus gas venting valve 108.

The gas metering unit 2 meters the anesthetic gases of oxygen and nitrous oxide whose individual through-flow quantities are displayed by means of through-flow measurement tubes (201, 211) and are adjustable via position valves (202, 212) driven by electric motors. The actuating variables for driving the position valves (202, 212) are supplied via the signal connections (848, 845) and are supplied by the oxygen concentration controller 206 and the breathing circuit volume controller 222.

The anesthetic agent metering unit 3 essentially comprises the anesthetic agent metering pump 307, which meters liquid anesthetic agents into the anesthetic gas line 112 where the liquid anesthetic agent vaporizes and mixes with the anesthetic gases (oxygen and nitrous oxide). Alternatively, the anesthetic agent can be injected directly into the breathing circuit 1 with an electrically-driven piston injector. The control of the anesthetic agent metering pump 307 takes place via the signal connection 856 which is connected with the anesthetic agent controller 302 and the amplifier 310.

The carbon dioxide control loop 4 comprises the carbon dioxide controller 402, the carbon dioxide sensor 107 as an actual value sensor and the level detector 110 for the breathing gas quantity in the breathing circuit 1. The actuating variable signal is supplied to the ventilator 101 via the connection 860 in the form of a ventilating frequency. The carbon dioxide concentration in the breathing circuit 1 is adjusted by changing the ventilating frequency.

The control unit 5 having an integrated computer portion is a desired value transmitter for the gas metering unit 2, the anesthetic agent metering unit 3, the carbon dioxide control loop 4 and the breathing stroke volume 816 of the ventilator 101. The signal lines for the following are connected to the control unit 5: breathing circuit volume desired value Vc SP (811), anesthetic gas desired value FG SP (812). oxygen concentration desired value O_2 SP (813); anesthetic agent concentration desired value A SP (814); carbon dioxide concentration desired value CO_2 SP (815) and breathing stroke volume desired value Vc SP (816).

A closed breathing circuit 1 is first assumed for operation; that is, as much anesthetic gas is delivered as is consumed and lost through leakage.

It is further assumed that an oxygen concentration desired value 813 and a breathing circuit volume desired value 811 are preset at the control unit 5. The anesthetic gas desired value 812 is set to zero for the closed breathing circuit 1 since the anesthetic gas quantity to be delivered is determined alone from the condition applying for the closed system, namely, that the oxygen concentration and the breathing circuit volume are to be held constant in the stationary case. The actual value in the breathing circuit is measured with the oxygen sensor 105 and supplied to the subtraction position 207 via the signal line 824. The output 833 is connected to the oxygen concentration controller 206. The level detector 110 supplies the actual value for the breathing circuit volume Vc and supplies the same to the subtraction position 221 via the signal line 821. The output 831 is connected to the breathing circuit volume controller 222.

The control signal for the anesthetic gas quantity, which must be metered into the breathing circuit 1 per unit of time to maintain the breathing circuit volume at the desired value 811, is formed at the output 832 of the addition position 216.

Specific actuating signals for the anesthetic gas are formed from the control signal at the output 832 and the oxygen concentration desired value 813 via the following: the multiplication position 205, the addition position 204 and the subtraction position 215. The actuating signals specific for the anesthetic gas are supplied to the signal connections (848, 845) of the positioning valves (202, 212) from the outputs 844, 847). The sum of the component gas flows (oxygen O_2 and nitrous oxide N_2O) measured at the throughflow measuring tubes (211, 201) is proportional to the control signal at the output 832. If this control signal is increased, the gas flows at the throughflow measurement tubes (211, 201) increase by the same amount. If in contrast, the oxygen concentration desired value 813 is changed, for example increased, then this leads to a correspondingly smaller control signal at the output 844 of the subtraction position 215; whereas, the control signal increases at the output of the adding position 204. The nitrous oxide positioning valve 212 is closed in that amount which the oxygen positioning valve 202 is opened. In contrast, the sum of the component gas flows measured at the throughflow measurement tubes (211, 201) remain constant. The limiters (203, 214) limit the signal voltages at the outputs (844, 847) to an upper and lower boundary value which is proportional to the minimal and maximal oxygen gas flow and nitrous oxide gas flow, respectively, which can be delivered.

The breathing gas volume controller 222 is configured as a proportional controller whole amplification is changeable via the characteristic transducer 224 in dependence upon the anesthetic gas flow signal 846. In the closed breathing circuit 1 wherein only the consumed

anesthetic gas is substituted, the amplification P of the breathing circuit volume controller **222** is a maximum and the sensitivity of the control loop is thereby likewise a maximum. The breathing loop volume control loop is the determining component for the anesthetic gas metering in the breathing circuit **1**. If in contrast thereto, the anesthetic gas desired value **812** is set high as, for example, for a half closed system, then the breathing circuit volume control loop becomes less significant since adequate anesthetic gas is always metered to the breathing circuit **1**. The limiter **223** limits the output signal **831** to the upper and lower value for the breathing circuit volume.

The anesthetic agent metering unit **3** adjusts a preselected concentration of he anesthetic agent. The anesthetic agent concentration desired value **814** is compared at the logic component **301** (subtraction position) with the actual value measured by the anesthetic agent sensor **106**. The signal line **823** conducting the actual value and the desired value **814** of the anesthetic agent concentration are connected to the limit value switch **312**.

The function of the limit value switch **312** will be described in the following.

If the difference signal between the desired value **814** and the actual value transmitted via the signal line **823** exceeds a preset upper limit value, then the limit value switch **312** supplies a control pulse to the disconnect switch **311** via the signal line **364** which then switches into the open position.

The input **852** of the amplifier **310** is connected with the anesthetic agent desired value **814**. If the amplification factor of the amplifier **310** is adjusted for example to a factor **10**, then the anesthetic agent is metered into the breathing circuit **1** in a quantity increased by a multiple of **10**.

If the difference signal at the limit value switch **312** drops beneath a lower preset limit value (that is, the new desired value in the breathing circuit **1** is almost reached), then the disconnect switch **311** switches to its closed position and the input **851** of the anesthetic agent controller **302** is connected with the output **834**. The anesthetic agent controller **302** thereby delivers the actuating variable **854** for the anesthesia agent metering unit **307**.

The limiter **303** limits the actuating variable **854** to the maximum adjustable concentration, for example to 6% by volume. The control signal **856** for the anesthetic agent metering unit **307** for the quantity of anesthetic agent to be delivered into the breathing circuit **1** is formed from the product **855** of the actuating variable **854** and the anesthetic gas flow FG (**846**) with this product **855** being formed at the multiplication portion **304**. The product **855**, charged with the metering rate **306**, provides the control signal **856** for the liquid quantity of anesthetic agent which is to be metered into the anesthetic gas line **112** by the anesthetic agent metering unit **3071** The anesthetic agent vapor together with the anesthetic gas is delivered via the anesthetic gas line **112** and the breathing anesthetic gas connection **111** to the circuit **1**.

The adjusting parameters of the anesthetic agent controller **302** can be influenced via the adaptation circuit **305**. The adaptation circuit **305** is connected via a signal line **866** to the control unit **5** and receives from the latter the desired values for the controller adjusting parameters (FIG. **3**). When the controller adjusting parameters are computed, the parameters related to the patient can also be considered which must be previously supplied to the control unit **5**.

With the combination of the limit value switch **312** and the disconnect switch **311**, it is intended that the anesthetic agent controller **302** be switched out for a certain time when changing the anesthetic agent desired value **814** and that the breathing circuit **1** be flushed with an anesthetic agent concentration deviating from the desired value. Only when the anesthetic agent concentration measured by the anesthetic agent sensor **106** has approximately reached the desired value **814**, will the anesthetic agent controller **302** again be switched in in order to control the anesthetic agent concentration to the precise value.

The carbon dioxide control loop **4** adjusts to a specific terminal expiratory carbon dioxide concentration. This parameter can essentially be influenced by the nature of the ventilation, for example, by the ventilating frequency at the ventilator **101**. The carbon dioxide desired value CO_2 SP (**815**) and the actual value signal transmitted by the signal line **822** are brought together at the subtraction position **401**. The actual value signal is supplied by the carbon dioxide sensor **107**. The control deviation at the output **835** is supplied to the carbon dioxide controller **402**. The signal at the output **859** is conducted via a limiter **403** which limits the variation range of the actuating variable on connection **860** to values which can be processed by the ventilator **101**. The actuating quantity on connection **860** is the ventilating frequency (f) of the ventilator **101**, that is, the number of strokes per minute. The amplification factor P of the carbon dioxide controller **402** is adjustable via the characteristic transducer **405**. The drive signal **867** for the characteristic transducer **405** is made up of the breathing minute volume signal M_v on signal line (**864**) formed at the multiplication position **404** and the breathing circuit volume signal V_c (**821**). The quotient of the breathing circuit volume signal V_c (**821**) and the breathing minute volume signal M_v (**864**) yield the drive signal T_3 (**867**) for the characteristic transducer **405**. The amplification factor and thereby the sensitivity are a maximum for a larger breathing minute volume signal on signal line **864**.

The control signal for the breathing stroke volume V_s (**816**) is supplied directly to the ventilator **101**.

An embodiment for the desired value change of the anesthetic agent concentration from S0 to S1 is shown in FIG. **2**. The curve A indicates the concentration in the breathing circuit with this concentration being measured by the anesthetic agent sensor **106**. Curve B is the anesthetic agent concentration in the anesthetic gas line **112** and curve C are the desired values S1 and S11 which are to be adjusted.

It is assumed that a change of anesthetic agent desired value **814** from S0 to S1 is pregiven at the control unit **5**. The limit value switch **312** registers a difference between the actual value measured by the anesthetic agent sensor **106** and the new desired value S1. Since the difference is above the preadjusted limit value, a control pulse is applied to the disconnect switch **311** via the output **364** which causes the disconnect switch to switch over into the open position shown in FIG. **1**. The anesthetic agent desired value **814** is connected to the input **852** of the amplifier **310**. By means of the amplifier, a dosage increased by the amplification factor and in a form of a flushing desired value S2 is adjusted at the anesthetic agent metering pump **307**. If the new desired value S1 is, for example, 0.5% by volume and

the amplification factor is 10, then anesthetic agent in the amount of 5% by volume is metered into the breathing circuit 1 as a flushing desired value S2.

The system parameters T2 and T1 (curve A) are determined from the discontinuous response of the anesthetic agent concentration measured by the anesthetic agent sensor 106. For a desired value change of S0 to S1, the time point is set to zero by a timing signal generator in the control unit 5. The concentration change measured by the anesthetic agent sensor 106 is continuously registered by the control unit 5 beginning from the start point. The system parameter T2 is then the time until the 0.1 portion of the desired value S1 is reached and the sum of T1 and T2 is the time until the 0.8 portion of the desired value S1 is reached. The system parameters T1 and T2 describe the instantaneous condition of the breathing circuit 1 and are dependent, for example, on the anesthetic gas flow metered by the gas metering unit 2 into the breathing circuit 1 and the ventilating parameters adjusted at the ventilator 101 such as the breathing frequency (f) and the breathing stroke volume V_s.

If the anesthetic agent concentration has reached the 0.9 portion of desired value S1, and thereby the point S3, then the disconnect switch 311 switches in the closure direction and the anesthetic agent controller 302 influences the anesthetic agent metering pump 307 for adjusting the new desired value in the breathing circuit 1.

From the measured system parameters T1 and T2, adjusting parameters for the anesthetic agent controller 302 are computed in the adaptation circuit 305 and impressed on the controller 302. For this purpose, it is advantageous to carry out portions of the computation in the control unit 5 and to transmit the signals via a control line 866 to the adaptation circuit 305. In addition, parameters of the patient can be inputted into the control unit 5 and considered when computing

The mathematical interrelationship between the system parameters T1 and T2 and the adjusting parameters (k, C_I, C_D) of the anesthetic agent controller 302 are given in FIG. 3. These computation formulas are based on the optimizing criteria of Ziegler and Nichols as described in the technical paper entitled "Optimum Setting for Automatic Controllers", Transaction of the A.S.M.E., November 1942.

The anesthetic ventilating apparatus of the invention is for administering anesthesia to a patient. The apparatus of the invention can, for example, include the following: a breathing circuit 1 for supplying respiratory gas containing an anesthetic agent to the patient and having first and second branches (113 and 114); a carbon dioxide absorber 102 disposed in one of said branches for removing carbon dioxide exhaled by the patient; a first control loop for generating a first actuating variable in response to which the amount of respiratory gas supplied to said breathing circuit 1 is adjusted; said first control loop including: an anesthetic gas metering unit 2 for receiving said first actuating variable and metering the respiratory gas into the breathing circuit 1 in response to said first actuating variable; and, an anesthetic gas controller 206 connected to said metering unit for operating on said first actuating variable and having a set of adjusting parameters; a second control loop for generating a second actuating variable in response to which the amount of anesthetic agent supplied to said breathing circuit 1 is adjusted; said second control loop including: an anesthetic agent metering unit 3 for receiving said second actuating variable and metering the anesthetic agent into the breathing circuit 1 in response to said second actuating variable; and, an anesthetic agent controller 302 connected to said metering unit for operating on said second actuating variable and having a set of adjusting parameters; a third control loop for generating a third actuating variable in response to which a ventilating frequency in said breathing circuit is adjusted; said third control loop including: a ventilating unit 101 for receiving said third actuating variable and adjusting said ventilating frequency in said breathing circuit in response to said third actuating variable; and, a carbon dioxide controller 402 connected to said ventilating unit 101 and having a set of adjusting parameters; coupling means (205, 224, 304, 305 and/or 405) for coupling two of said loops so as to permit one of said actuating values to change another one of said actuating values; a control unit 5 for supplying: an anesthetic gas desired value to said first control loop; an anesthetic agent desired value to said second control loop; and, a carbon dioxide desired value to said third control loop; said control unit 5 including means for changing one of said desired values from a desired first value to a desired second value in a discontinuous jump-like manner; an oxygen sensor 105 of said first control loop for measuring the anesthetic gas actual value present in said breathing circuit 1; an anesthetic agent sensor 106 of said second control loop for measuring the anesthetic agent actual value present in said breathing circuit 1; a carbon dioxide sensor 107 of said third control loop for measuring the carbon dioxide actual value present in said breathing circuit; a logic component (207, 301 or 401) for receiving one of said desired values for one of said control loops and one of said actual values corresponding to said one control loop for forming a closed loop control signal; switch means 311 switchable between an open position wherein said one control loop is opened and connected to said control unit 5 for receiving and applying said desired second value to said unit of said one control loop and a closed position wherein said one control loop is closed and connected to said logic component for receiving and applying said closed loop control signal to the controller of said one control loop; limit means 312 responding to said change from said desired first value to said desired second value for switching said switch means 311 from said closed position to said open position for a predetermined time duration; said control unit 5 including processing means monitoring the sensor corresponding to said one control loop for determining breathing circuit system parameters T1 and T2 and computing said adjusting parameters of the controller of said one control loop; and, said limit means 312 being connected to the one sensor of said one control loop and responding to a predetermined value measured by said one sensor for switching said switch means back into said closed position so as to permit said controller of said one control loop to adjust the actuating variable of said one control loop so as to cause said unit of said one control loop to readjust the concentration of the substance measured by said one sensor to said first desired value.

It is understood that the foregoing description is that of the preferred embodiments of the invention and that various changes and modifications may be made thereto without departing from the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. Anesthetic ventilating apparatus for administering anesthesia to a patient, the apparatus comprising:

a closed-loop breathing circuit for supplying and recirculating respiratory gas containing an anesthetic agent to the patient and having first and second branches;

a carbon dioxide absorber disposed in one of said branches for removing carbon dioxide exhaled by the patient;

a gas metering unit supplying anesthetic gases into said breathing circuit;

said gas metering unit including: an oxygen sensor for measuring the oxygen content in said breathing circuit; and, an oxygen concentration controller connected to said oxygen sensor for determining the quantity of oxygen to be metered into the breathing circuit and for generating a first actuating variable in response to which oxygen is supplied to said breathing circuit;

said gas metering unit further including: a level detector for measuring the breathing circuit volume; and, a breathing circuit volume controller connected to said level detector for generating a second actuating variable in response to which anesthetic gas is supplied to said breathing circuit;

an anesthetic agent metering unit for generating a third actuating variable in response to which the amount of an anesthetic agent supplied to said breathing circuit is adjusted;

an anesthetic agent controller connected to said anesthetic agent metering unit and having a set of adjusting parameters;

coupling means for coupling two of said controllers so as to permit one of said actuating values to change another one of said actuating values;

a control unit for changing the concentration of the anesthetic agent supplied by said anesthetic agent metering unit from a first desired value S1 to a second desired value S2 in a discontinuous jump-like manner with said second desired value S2 being a flushing concentration by volume of said anesthetic agent which is many times greater than the concentration by volume of said anesthetic agent corresponding to said first desired value S1;

said anesthetic agent metering unit with said anesthetic agent controller and said control unit conjointly defining a normally closed control loop;

an anesthetic agent sensor for measuring the anesthetic agent actual value present in said breathing circuit;

a logic component for receiving said first desired value S1 of said anesthetic agent and said anesthetic agent actual value for forming a closed loop control signal;

said control unit including:

(a) limit means for registering a difference between said actual value and said first desired value S1 of anesthetic agent in said breathing circuit and for emitting an output signal for a predetermined duration when said difference exceeds a predetermined limit;

(b) a disconnect switch having an output and being switchable in response to said output signal from a first position wherein said normally closed control loop is closed and wherein said logic component is connected to said anesthetic agent controller for applying said closed loop control signal thereto to a second position wherein said normally closed control loop is opened and wherein said first desired value S1 is applied to said output; and,

(c) amplifier means connected to said output of said disconnect switch for receiving said desired value S1 when said disconnect switch is in said second position and having an amplification for amplifying said first desired value S1 many times to form said second desired value S2 indicative of said flushing concentration of said anesthetic agent;

said control unit further including processing means monitoring the concentration of the anesthetic agent measured by said anesthetic agent sensor for determining first and second breathing circuit system parameters (T1 and T2) and for computing said adjusting parameters for said anesthetic agent controller;

said first breathing circuit parameter T1 representing the time to reach a first percentage value of the desired anesthetic concentration and said second breathing circuit parameter T2 representing the time required to reach a second percentage value of the desired anesthetic concentration starting from an initial value SO of anesthetic medium in said breathing circuit;

said limit means being connected to said anesthetic agent sensor and responding to a predetermined value S3 of the concentration of said anesthetic agent in said breathing circuit for switching said disconnect switch back into said first position so as to permit said anesthetic agent controller to adjust said second actuating variable so as to cause said anesthetic agent metering unit to readjust the concentration of said anesthetic agent to said first desired value S1;

the concentration of said anesthetic agent S3 corresponding to approximately (0.9) (S1) when the concentration of the agent is increased and corresponding to approximately (1.1) (S11) when the concentration of the agent is reduced, said S11 being a new desired value applied to said normally closed control loop by said control unit when said disconnect switch is again in said first position;

said system parameter T2 corresponding to the time required to achieve said concentration of approximately (0.1) (S1) when increasing the concentration of the agent in said breathing circuit; and,

the sum of said system parameters (T1+T2) corresponding to the time required to achieve approximately (0.8) (S1) when increasing the concentration of the agent in said breathing circuit.

2. The anesthetic ventilating apparatus of claim 1, said amplification being selected for amplifying said value S2 up to ten times when increasing the concentration of said anesthetic agent in said breathing circuit thereby permitting said value S2 to be adjusted up to ten times of said value S1 and for reducing said value S2 to zero when reducing the concentration of said anesthetic agent in said breathing circuit.

3. The anesthetic ventilating apparatus of claim 1, wherein said coupling means is a transducer connected between two of said controllers.

4. The anesthetic ventilating apparatus of claim 1, wherein said control unit supplies desired values to respective ones of said controllers corresponding to said actuating variables; and, said control unit including

sequence control means for fixing the sequence with which said desired values are applied.

5. The anesthetic ventilating apparatus of claim 4, further comprising a carbon dioxide control loop for adjusting the ventilating rate in said breathing circuit; and, wherein the respiratory gas includes oxygen as a component and wherein said gas metering unit includes oxygen supply means for adjusting the supply of oxygen contained in said respiratory gas; and, wherein said sequence control means is adapted to first operate on said oxygen supply means of said gas metering unit to first adjust the oxygen concentration in said breathing circuit; to thereafter operate on said anesthetic metering unit to adjust the concentration of anesthetic agent in said breathing circuit to thereby adjust the depth of the anesthesia; and to then operate on said carbon dioxide control loop to adjust the ventilating rate in said breathing circuit.

6. Anesthetic ventilating apparatus for administering anesthesia to a patient, the apparatus comprising:

a closed-loop breathing circuit for supplying respiratory gas containing an anesthetic agent to the patient and having first and second branches;

a carbon dioxide absorber disposed in one of said branches for removing carbon dioxide exhaled by the patient;

a first closed control loop for generating a first actuating variable in response to which the amount of respiratory gas supplied to said breathing circuit is adjusted;

said first closed control loop including: an anesthetic gas metering unit for receiving said first actuating variable and metering the respiratory gas into the breathing circuit in response to said first actuating variable; and, an anesthetic gas controller connected to said metering unit for operating on said first actuating variable and having a set of adjusting parameters; a second closed control loop for generating a second actuating variable in response to which the amount of anesthetic agent supplied to said breathing circuit is adjusted;

said second closed control loop including: an anesthetic agent metering unit for receiving said second actuating variable and metering the anesthetic agent into the breathing circuit in response to said second actuating variable; and, an anesthetic agent controller connected to said metering unit for operating on said second actuating variable and having a set of adjusting parameters;

a third closed control loop for generating a third actuating variable in response to which a ventilating frequency in said breathing circuit is adjusted;

said third closed control loop including: a ventilating unit for receiving said third actuating variable and adjusting said ventilating frequency in said breathing circuit in response to said third actuating variable; and, a carbon dioxide controller connected to said ventilating unit and having a set of adjusting parameters;

coupling means for coupling two of said loops so as to permit one of said actuating values to change another one of said actuating values;

a control unit for changing the concentration of the anesthetic agent supplied by said anesthetic agent metering unit from a first desired value S1 to a second desired value S2 in a discontinuous jump-like manner with said second desired value S2 being a flushing concentration by volume of said anesthetic agent which is many times greater than the concentration by volume of said anesthetic agent corresponding to said first desired value S1;

said anesthetic agent metering unit with said anesthetic agent controller and said control unit conjointly defining said second closed control loop as a normally closed control loop;

an oxygen sensor of said first control loop for measuring the anesthetic gas actual value present in said breathing circuit;

an anesthetic agent sensor of said second control loop for measuring the anesthetic agent actual value present in said breathing circuit;

a carbon dioxide sensor of said third control loop for measuring the carbon dioxide actual value present in said breathing circuit;

a logic component for receiving said first desired value S1 of said anesthetic agent and said anesthetic agent actual value for forming a closed loop control signal;

said control unit including:

(a) limit means for registering a difference between said actual value and said first desired value S1 of anesthetic agent in said breathing circuit and for emitting an output signal for a predetermined duration when said difference exceeds a predetermined limit;

(b) a disconnect switch having an output and being switchable in response to said output signal from a first position wherein said normally closed control loop is closed and wherein said logic component is connected to said anesthetic agent controller for applying said closed loop control signal thereto to a second position wherein said normally closed control loop is opened and wherein said first desired value S1 is applied to said output; and,

(c) amplifier means connected to said output of said disconnect switch for receiving said desired value S1 when said disconnect switch is in said second position and having an amplification for amplifying said first desired value S1 many times to form said second desired value S2 indicative of said flushing concentration of said anesthetic agent;

said control unit further including processing means monitoring the concentration of the anesthetic agent measured by said anesthetic agent sensor for determining breathing circuit system parameters T1 and T2 and computing said adjusting parameters of said anesthetic agent controller of said second closed control loop;

said first breathing circuit parameter T1 representing the time to reach a first percentage value of the desired anesthetic concentration and said second breathing circuit parameter T2 representing the time required to reach a second percentage value of the desired anesthetic concentration starting from an initial value SO of anesthetic medium in said breathing circuit;

said limit means being connected to said anesthetic agent sensor and responding to a predetermined value S3 of the concentration of said anesthetic agent in said breathing circuit for switching said disconnect switch back into said first position so as to permit said anesthetic agent controller to adjust said second actuating variable so as to cause said anesthetic agent metering unit to readjust the con-

centration of said anesthetic agent to said first desired value S1;

the concentration of said anesthetic agent S3 corresponding to approximately (0.9) (S1) when the concentration of the agent is increased and corresponding to approximately (1.1) (S11) when the concentration of the agent is reduced, said S11 being a new desired value applied to said normally closed control loop by said control unit when said disconnect switch is again in said first position;

said system parameter T2 corresponding to the time required to achieve said concentration of approximately (0.1) (S1) when increasing the concentration of the agent in said breathing circuit; and,

the sum of said system parameters (T1+T2) corresponding to the time required to achieve approximately (0.8) (S1) when increasing the concentration of the agent in said breathing circuit.

7. The anesthetic ventilating apparatus of claim 6, said coupling means being a transducer coupling two of said loops.

8. The anesthetic ventilating apparatus of claim 7, said transducer being a first transducer coupling said first and second control loops and said apparatus further including a second transducer for coupling said second and third loops.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,094,235

DATED : March 10, 1992

INVENTOR(S) : Dwayne D. Westenskow, Patrick J. Loughlin, Roman R. Jaklitsch and Carl-Friedrich Wallroth

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In column 4, line 60: delete "CI, CD" and substitute -- C_I, C_D -- therefor.

In column 6, line 5: delete "." and substitute -- , -- therefor.

In column 6, line 43: before "848, 847)", insert -- (--.

In column 7, line 53: delete "portion" and substitute -- position -- therefor.

In column 7, line 58: delete "3071" and substitute -- 307. -- therefor.

In column 7, line 60: delete "breathing".

In column 7, line 61: before "circuit 1", insert -- breathing --.

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,094,235

DATED : March 10, 1992

INVENTOR(S) : Dwayne D. Westenskow, Patrick J. Loughlin, Roman R. Jaklitsch and Carl-Friedrich Wallroth

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In column 9, line 38: after "computing", insert -- the adjusting parameters. --.

In column 13, line 38: after "parameters;", start a new paragraph.

Signed and Sealed this

Twenty-second Day of June, 1993

Attest:

Michael K. Kirk

MICHAEL K. KIRK

Attesting Officer

Acting Commissioner of Patents and Trademarks